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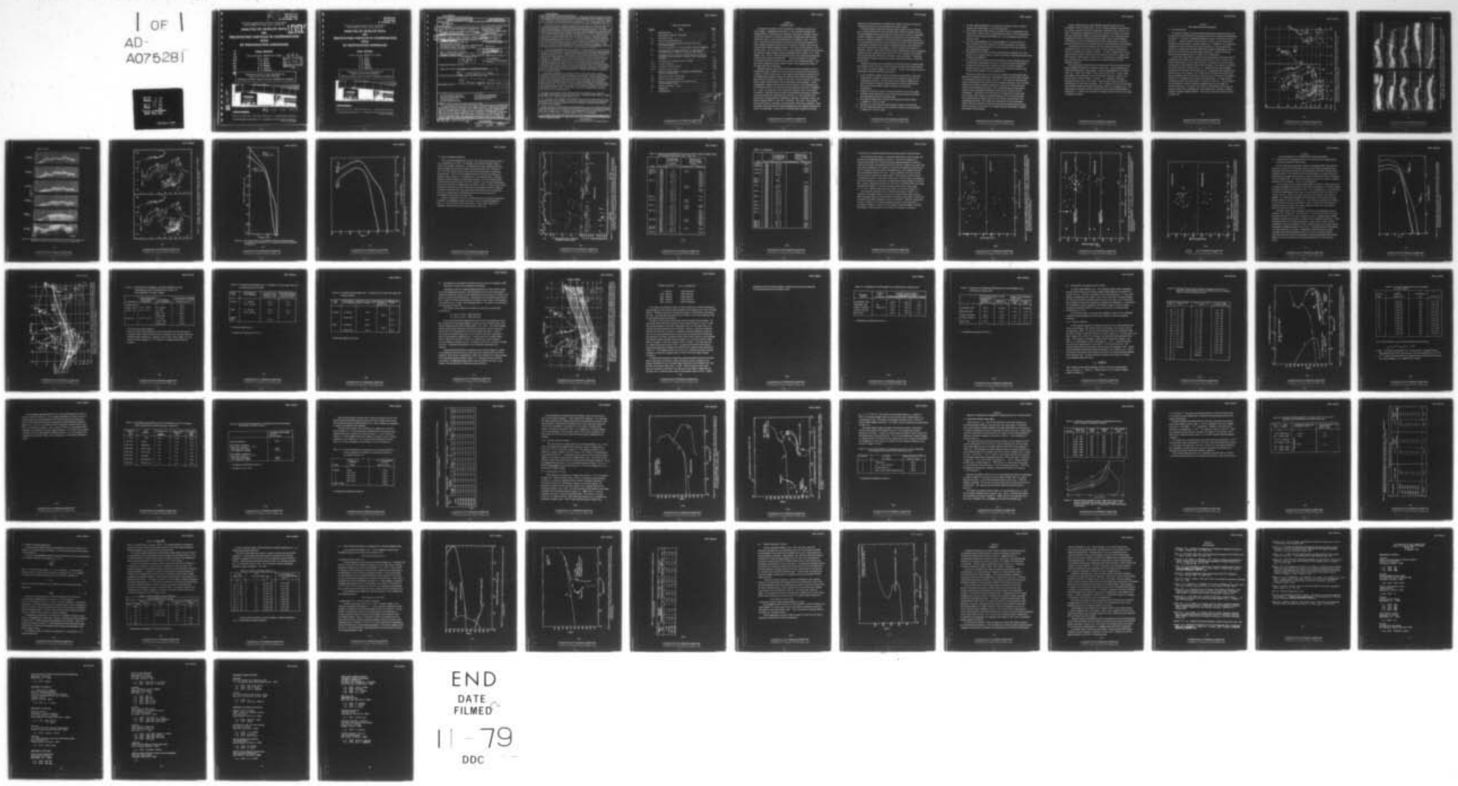

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LEVEL II

ANALYSIS OF SATELLITE DATA ON PRECIPITATING PARTICLES IN COORDINATION WITH ELF PROPAGATION ANOMALIES

AD A075281

FINAL REPORT

Contract Number N00014-75-C-0954

W. L. Imhof
T. R. Larsen
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R. C. Gunton
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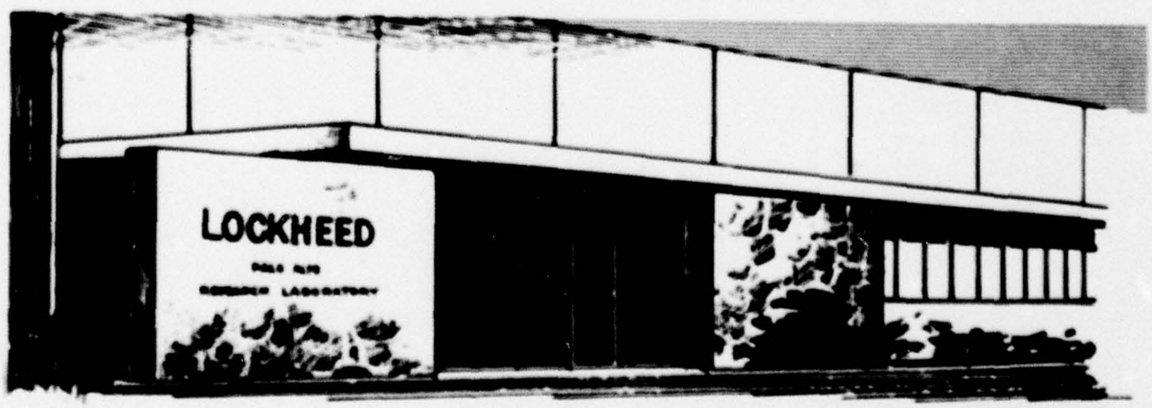

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Precipitating electrons	Solar particle events
Ion-pair production rates	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An investigation has been made of the effects of energetic particle precipitation into the atmosphere on the transmission of ELF signals based on coordinated data acquired during the Greenland Sea exercise in 1977, and at other times. The energetic particle data were obtained with the Lockheed payload on the polar-orbiting satellite 1972-076B, and the ELF signal strength data were provided by P. R. Bannister at the Naval Underwater Systems Center near New London, Connecticut. In the Greenland Sea exercise significant fluxes of precipitating electrons were measured on many of the satellite passes and unusually high intensities were observed on several occasions, → next page

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two of which were selected for special study. A search was made for possible correlation between electron precipitation and ELF signal strength, but no evidence was found for a consistent variation between the two parameters. This finding may partly reflect the uncontrolled and variable receiving conditions during the Greenland Sea exercise.

For two of the major electron precipitation events observed in the April-May 1977 Greenland Sea exercise, detailed analyses were performed of the electron energy spectra and intensities, and of the resulting energy deposition profiles. For each of the electron density profiles, calculations of the ELF signal strengths were performed with the waveguide-mode computer program developed at the Naval Ocean Systems Center. From these calculations taken together with computations for other events it became clear that the received signal may either increase or decrease, depending upon the spatial extent and location of ionization. The predicted effects of a single relativistic electron precipitation event are not severe, but due to their frequent occurrence they may provide the opportunity to verify experimentally the predicted effects of more severe and rarely occurring phenomena such as solar particle events. For a more precise evaluation of their continued role in regard to ELF propagation, the acquisition and analysis of data on more coordinated passes should be performed.

For electron precipitation events attempts were made to take better account of the full transmission geometry. The calculations were performed with position-dependent ionospheric electron and ion profiles for the satellite pass on 26 March 1976 during an electron precipitation event. During that pass two electron energy spectra were deduced and energy deposition rates and electron and ion density profiles deduced for both spectra. Assuming that the electron precipitation occurred uniformly along the L shells at all longitudes covered by the ELF paths under study, the two sets of ionospheric profiles were applied to the various portions of the propagation paths. The calculations so performed provided very good agreement with the measurements at Maryland and Tromso, whereas for Thule and Pisa the results were less satisfying. The lack of agreement may indicate that ambient nighttime conditions were not applicable to the entire paths and that in general more complete information is needed all along a propagation path.

Additional calculations were made for solar particle event (SPE) conditions, including for the first time daytime conditions. Specifically, electron and ion density profiles for the SPE of 4 August 1972 at 1144 UT were used. Electron densities above 59 km were derived from incoherent scatter radar observations made at Chatanika. Electron and ion densities down to 40 km were calculated using an ion chemistry model, and ion densities below 40 km were calculated assuming loss of charge by ion neutralization only. The results, calculated for daytime conditions, indicated slightly more attenuation than earlier calculations for SPE nighttime conditions. In other calculations for SPE events a considerable sensitivity to changes in ion density profiles below 35 km was demonstrated.

The effect of variation of solar zenith angle and ion chemistry over a long ELF propagation path from WTF to Tromso under SPE conditions was found to have a significant effect on ELF signal strength at the receiver.

The waveguide mode computer code originally used 32 amu for ionic masses to compute conductivites at all altitudes. When a more realistic variation of ionic mass was introduced, the resulting attenuation for SPE conditions over the path from WTF to Tromso was little changed.

During an electron precipitation event bremsstrahlung x-rays are produced which penetrate the atmosphere and can produce ion production rates between 35 and 60 km greater that those of cosmic rays. In one such case inclusion of the x-ray source led to an increase in attenuation over a nighttime path from WTF to Connecticut.

In a further study of sporadic E layer effects, an experimental profile superimposed on ambient nighttime conditions at 118 km led to a reduction in received signal strength over the WTF to Connecticut path.

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Section 1
INTRODUCTION

Extremely low frequency (ELF) transmission at nighttime is known to be quite variable. Transmissions from the U.S. Navy operated Wisconsin Test Facility (WTF) to receiving sites in Connecticut, Maryland, Greenland, Norway, and Italy are observed to experience anomalous and significant signal strength reductions of up to $\approx$ 3 db on approximately 60 to 80 nights per year. In recent years, it has been recognized that at least some of the observed anomalies are due to enhanced ionization caused by the precipitation of energetic electrons and protons into the earth's atmosphere (Davis, 1974, 1976; Davis and Meyers, 1975; Larsen, 1974). For the first time in 1976, a successful correlation was made between the anomalous signal strength and the precipitating particles (Imhof, et al., 1976; Reagan, et al., 1978a). This was based primarily on the measured transmissions between the Wisconsin Test Facility (WTF) and the mid-latitude receiving site in Connecticut and direct satellite measurements of precipitating particles. This preliminary finding has formed a basis for further more quantitative studies of the cause-and-effect relationship.

Subsequent studies of the effects of energetic particle precipitation on ELF transmission signal strength have been made at the Lockheed Palo Alto Research Laboratory (LPARL) based partly on data acquired with scientific payloads on the low altitude polar orbiting satellites 1971-089A and 1972-076B developed by the Space Sciences Laboratory of LPARL for the Office of Naval Research, the Defense Nuclear Agency and the Defense Advanced Research Projects Agency. In these investigations, supported by the Office of Naval Research, ELF propagation data were obtained from Dr. John Davis of the Naval Research Laboratory, Washington, D.C., and P. R. Bannister of Naval Underwater Systems Center, New London, Connecticut. This large data set includes measurements taken during coordinated exercises involving ELF transmission between the U.S. Navy Wisconsin Test Facility and receiving stations in Connecticut, Maryland, Greenland, Norway, and Italy performed in March - April 1975, and March - April 1976. These studies have provided further verification of the importance of particle precipitation. Since the details of the horizontal and vertical distributions of the enhanced ionization are clearly very important, a large body of coordinated data is required to provide

quantitative interpretations of the results and to assess the impact of important chemistry parameters on the transmitted ELF signal strength.

With the energetic particle data obtained from payloads on the low altitude polar-orbiting satellites 1971-089A and 1972-076B, in 1976 a qualitative correlation was established between anomalous ELF signal levels received at Connecticut and the precipitation of significant fluxes of electrons from the radiation belts. However, a detailed quantitative correlation between the sign (signal enhancement versus degradation) and severity of the anomalies and particle characteristics such as intensities and spectra was not firmly established because of the limited data base used. Stimulated by these findings, special coordinated exercises were conducted in March - April 1976 involving satellite measurements of the precipitating particles and ELF transmissions between the U.S. Navy Wisconsin Test Facility and receiving stations in Maryland, Greenland, Norway, and Italy. Coordinated satellite/ELF transmission measurements were also made in March - April 1975 and July 1975.

Detailed discussions of the investigations performed from the coordinated data sets acquired in 1975 and 1976 are provided in the previous annual reports (Imhof, et al., 1976, 1977) and bv Reagan, et al. (1978a). Briefly, the following major conclusions have followed from these study efforts:

- From coordinated satellite and ELF attenuation measurements, it has been found that direct particle precipitation into the atmosphere can cause ELF transmission anomalies. In these anomalies the signal strengths may be either attenuated or enhanced depending upon the geometry and details of the ion and electron density profiles resulting from the particle precipitation.
- Sensitivity studies were made to assess the dependence of the ELF signal strengths on such parameters as the electron and ion density profiles and their distribution along the propagation path.
- The signal strengths tend to decrease with increasing electron density at altitudes of ~ 60 km or lower.
- The effect of a given ionization profile depends strongly on its location.
- The ELF signal strengths are most sensitive to positive ion density profiles at altitudes of ~ 45 km or lower.

- The ELF signal strengths are very sensitive to sporadic E-layers, with the altitude of the ledge being a very critical parameter.
- The measured and predicted effects of energetic electron precipitation events can provide a readily available verification of the effects on ELF transmission of more rarely occurring and possibly more severe phenomena such as solar particle events.
- Variations in the nighttime ELF signal strengths on a fine time scale are observed which may be due entirely to electron precipitation, but cannot be accounted for quantitatively due to present limitations in the measurements and computational techniques.
- The geometry for the effect of electron precipitation on nighttime ELF transmission is very complex and as a result the following recommendations were made for future investigations:
- New techniques for mapping electron precipitation profiles simultaneously over a broad spatial region should be used in a coordinated measurement program.
- Existing ELF waveguide-mode computer programs should be modified to include treatment of variations in the electron and ion density profiles along a direction perpendicular to the propagation path.

The purpose of this report is to present the findings of an investigation undertaken with coordinated satellite-ELF transmission measurements performed during the Greenland Sea exercise in April - May 1977. At the same time that the transmission measurements were performed, the Lockheed experiment on the 1972-076B satellite was operated in special coordination to measure the fluxes and energy spectra of the precipitating electrons. This coordinated data set encompassed periods of major geomagnetic disturbance and moderately intense electron precipitation. Calculations of the expected ELF attenuations were made using the waveguide model computer program developed at the Naval Ocean Systems Center and ionization profiles derived from the satellite measurements of the precipitating electrons. The results have confirmed the previous conclusion that the electron precipitation events occurring along the signal path may lead to either an increase or a decrease in ELF signal attenuation depending on intensity and location of the ionization.

Further studies have been made with data acquired during the electron precipitation event of 26 March 1976. The ELF signal propagation was calculated for a number of paths, from WTF to Maryland, Connecticut, Pisa, Tromso, and Thule. The paths were segmented to take into account the variations of ionization and earth conductivity along the direction of propagation. The results have again emphasized the need for complete information along the path and the difficulty of obtaining it in electron precipitation events with a limited number of satellite passes and without the use of a widespread x-ray mapping technique from a satellite.

Calculations were also performed of the ELF signal transmission from the transmitter at WTF to a receiver at Tromso, Norway during a simulated solar particle event (SPE) under daytime conditions. For these calculations the ion and electron density altitude profiles were based largely on the SPE of 4 August 1972. These daytime results predict a large increase in attenuation over ambient nighttime conditions and a smaller increase over a similar calculation for SPE nighttime conditions.

The experimental results during the Greenland Sea Exercises and the various signal strength calculations are presented in this report. Many individuals have contributed significantly to this program. Special acknowledgments are extended to Mr. R. G. Joiner of the Office of Naval Research and to Dr. T. Quinn, while at the Office of Naval Research, for their important cooperation, support, and direction under Contract N00014-75-C-0954. P. R. Bannister at the Naval Underwater System Center, New London, Connecticut generously provided the experimental ELF data used in this study. Mr. W. Moler of the Naval Ocean System Center (NOSC) kindly cooperated in providing the NOSC wave propagation code. We acknowledge the cooperation of the Norwegian Defence Research Establishment in granting Dr. T. Larsen a leave of absence to engage in this ELF study activity while in residence at LPARL.

Section 2

THE GREENLAND SEA EXERCISE

2.1 The Satellite Data

The spatial coverage of the data acquired during selected coordinated passes of the satellite in the April-May 1977 Greenland Sea exercise is illustrated schematically in Figure 2-1. The area of coordination during the exercise is indicated by the broken lines. Several examples of the energetic (> 150 kev) electron flux profiles measured from the satellite are shown in Figure 2-2. In addition to the counting rate modulation normally associated with trapped electrons, on certain spins of the satellite the counting rates remained high during the upward viewing of the electron spectrometer indicating an isotropic angular distribution. This means that the fluxes of precipitating electrons were equal to the trapped fluxes.

Surveys were made of the precipitating electron and proton data taken during 92 acquisitions of the satellite 1972-076B in the time period 15 April to 20 May 1977. In these detailed surveys strip plots were made of the outputs of 5 electron spectrometers and one proton detector in the ARPA-501 payload. An example of a portion of one of these surveys is shown in Figure 2-3. Significant fluxes of precipitating electrons were measured on many of the passes, and unusually high intensities were observed on several occasions - two of which have been selected for special study. The precipitating electron flux profiles measured on two of the passes are plotted in Figure 2-4 on a schematic presentation of the satellite path. For these electron precipitation events, the energy spectra are shown in Figure 2-5. The two spectra are quite different, with one containing significant intensities at energies of several hundred keV. For each of these electron energy spectra the ion-electron production rates in the atmosphere have been calculated as a function of altitude, using the computer program AURORA. The ion pair production profiles are shown in Figure 2-6.

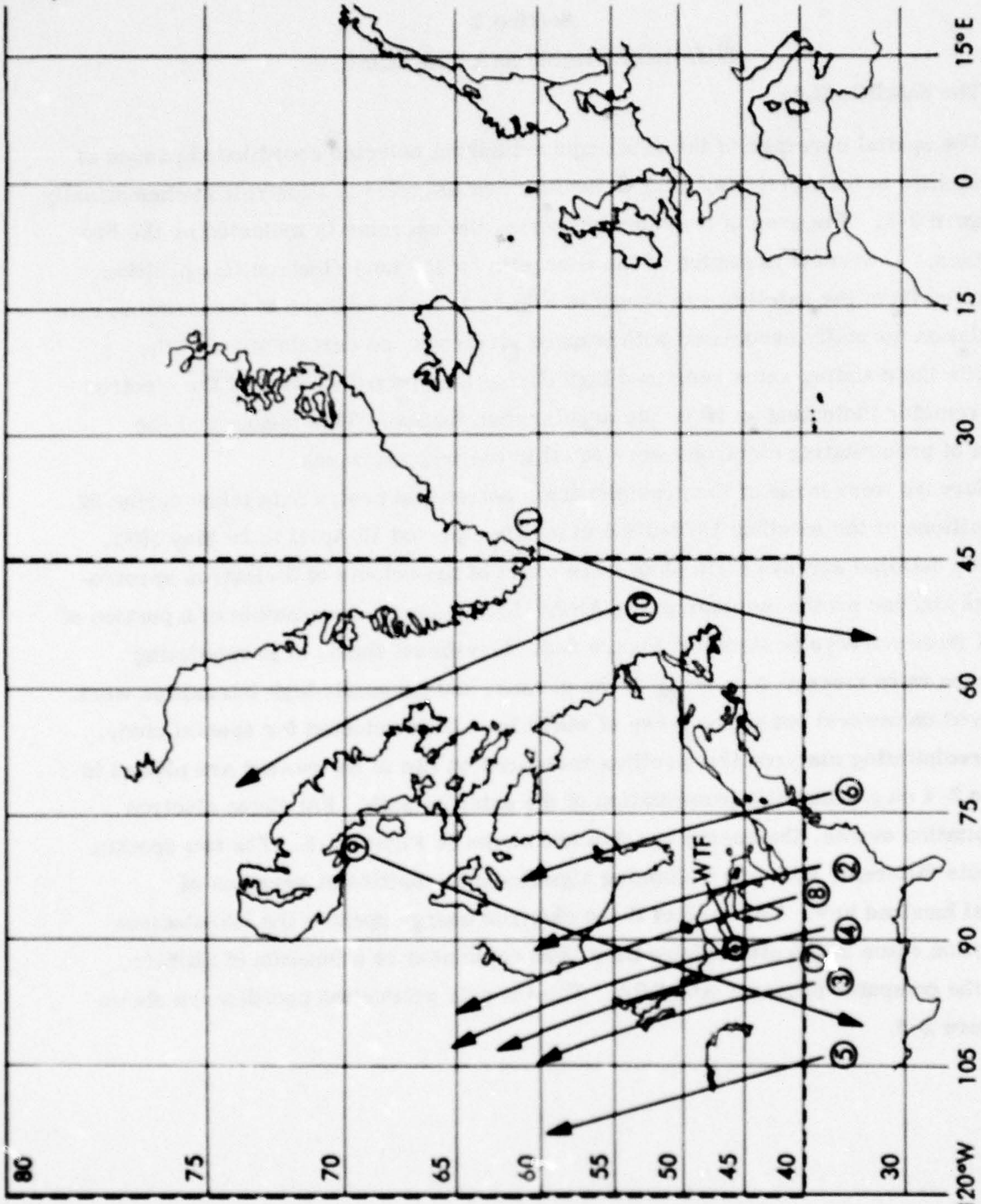

Figure 2-1 Schematic illustration of the spatial coverage of data acquired during selected coordinated passes of the satellite in the April-May 1977 Greenland Sea exercise. The area of coordination is indicated by the broken lines

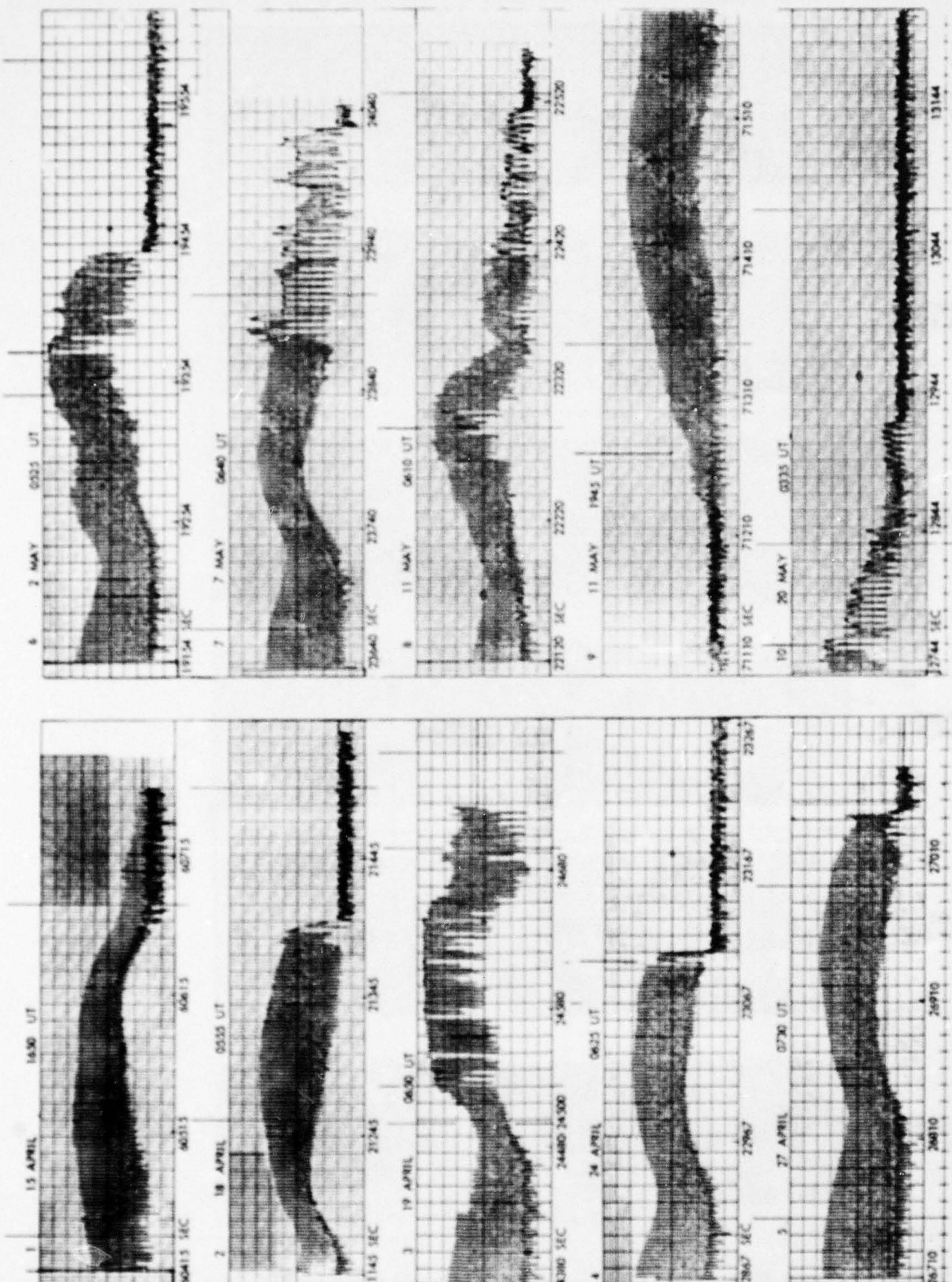

Figure 2-2 Examples of energetic (>150 Kev) electron flux profiles measured from the satellite during the April-May, 1977 Greenland Sea exercise. At times of high flux one can often see the counting rate modulation associated with the 5 second spin period of the satellite.

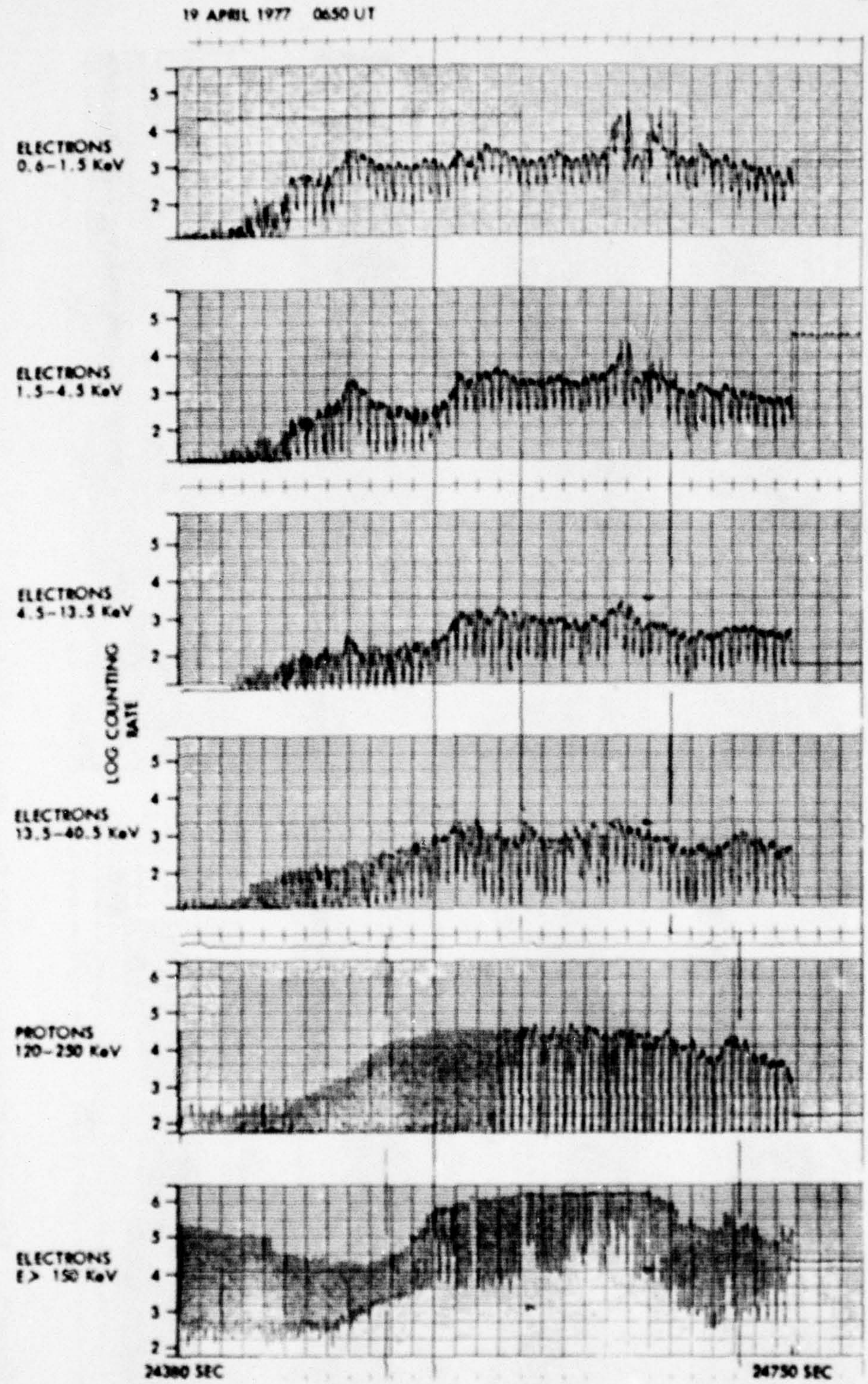

Figure 2-3 Examples of surveys of precipitating electron and proton data from satellite 1972-076B in the time period 15 April to 20 May 1977

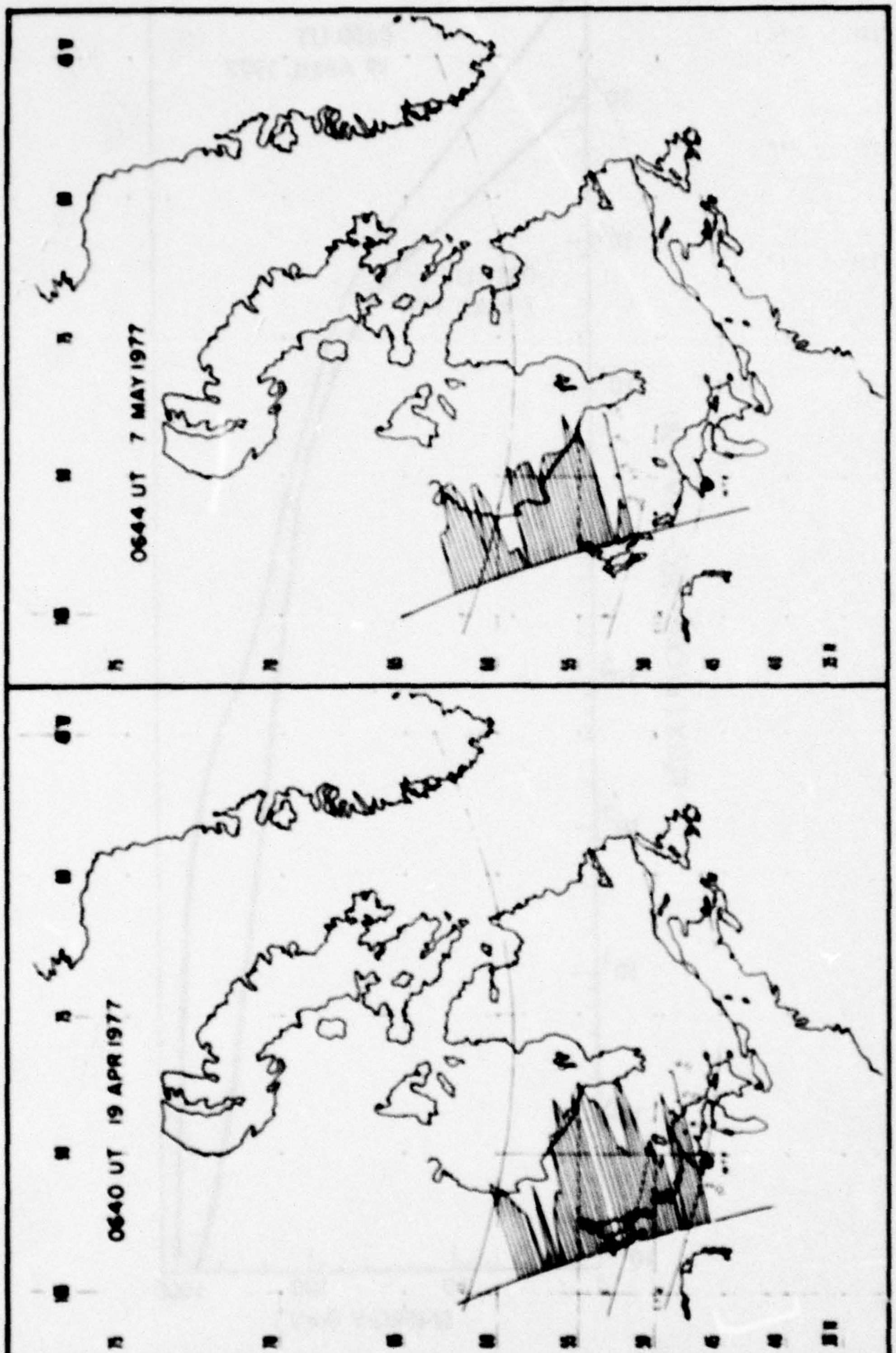

Figure 2-4 Schematic illustration of two satellite passes during the April-May 1977 coordinated exercises. The flux profiles of electrons > 150 keV are also shown.

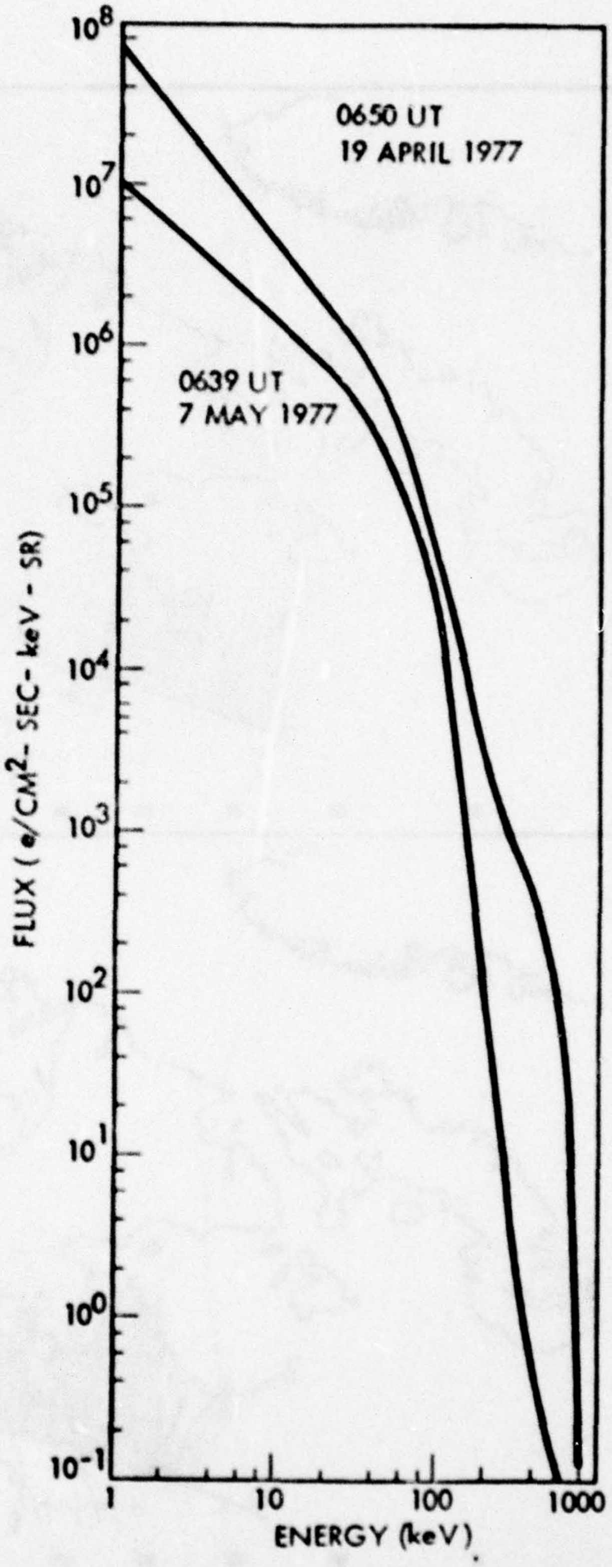

Figure 2-5 The energy spectra of precipitating electrons measured during two events in the April-May 1977 coordinated exercises illustrated in Figure 2-4.

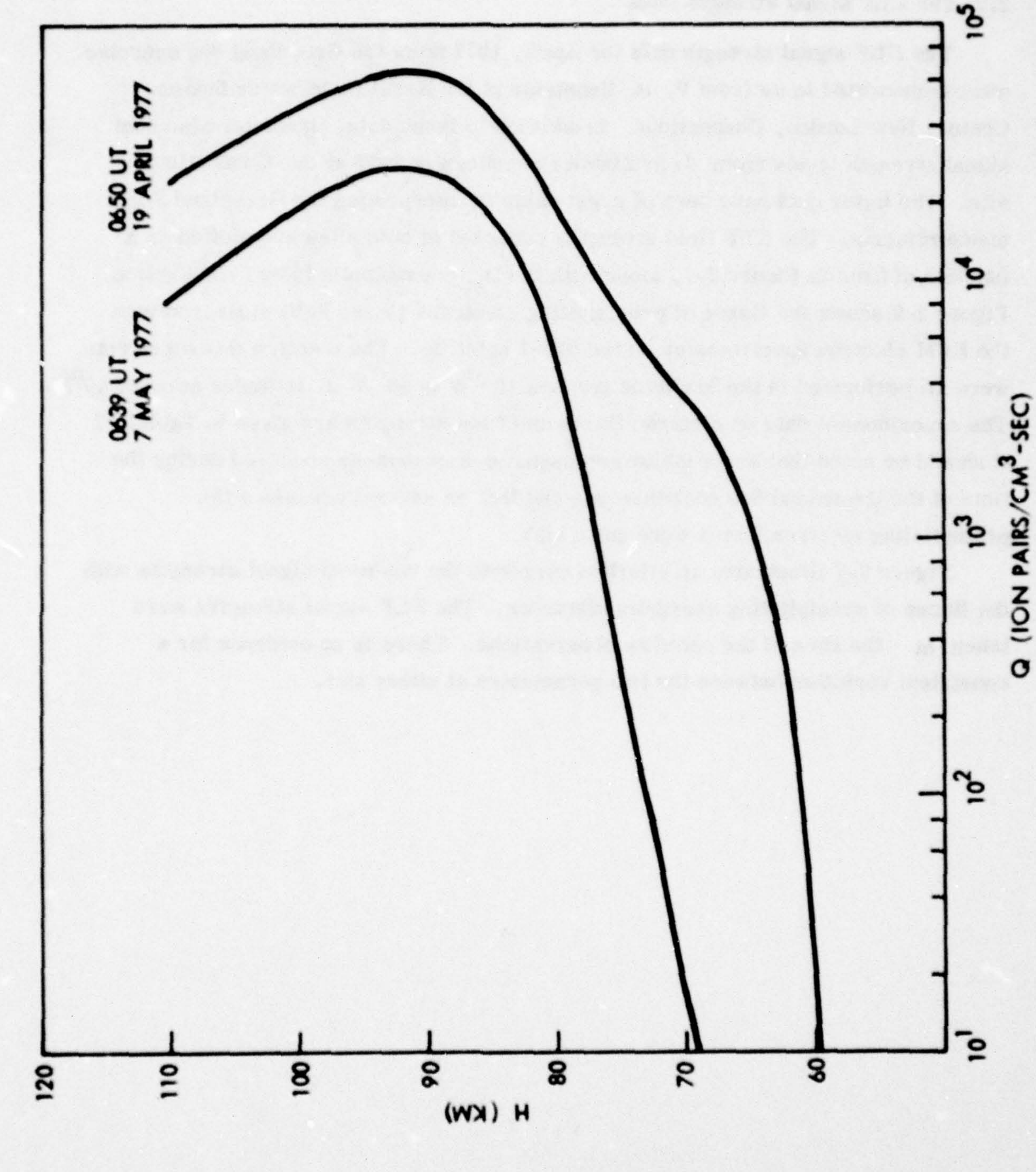

Figure 2-6 Ion pair production profiles for two events in the April–May 1977 coordinated exercises illustrated in Figure 2-4.

2.2 The ELF Signal Strength Data

The ELF signal strength data for April, 1977 from the Greenland Sea exercise were transmitted to us from P. R. Bannister at the Naval Underwater System Center, New London, Connecticut. In addition to these data, Bannister also sent signal strength levels from all available recordings in 1977 at the Connecticut site. The latter data have been of great value in interpreting the Greenland Sea measurements. The ELF field strengths recorded at both sites are plotted as a function of time in Figure 2-7, along with the D_{st} geomagnetic index. In addition, Figure 2-7 shows the fluxes of precipitating electrons (> 150 keV) measured with the EEM electron spectrometer on the S72-1 satellite. The electron measurements were all performed in the longitude interval 120°W to 45°W at latitudes north of 40°N. The experimental data on electron fluxes and field strengths are given in Table 2-1. It should be noted that some major geomagnetic disturbances occurred during the time of the Greenland Sea coordinations and that on several occasions the precipitating electron fluxes were quite high.

Figure 2-7 illustrates an effort to correlate the observed signal strengths with the fluxes of precipitating energetic electrons. The ELF signal strengths were taken at the time of the satellite observations. There is no evidence for a consistent variation between the two parameters at either site.

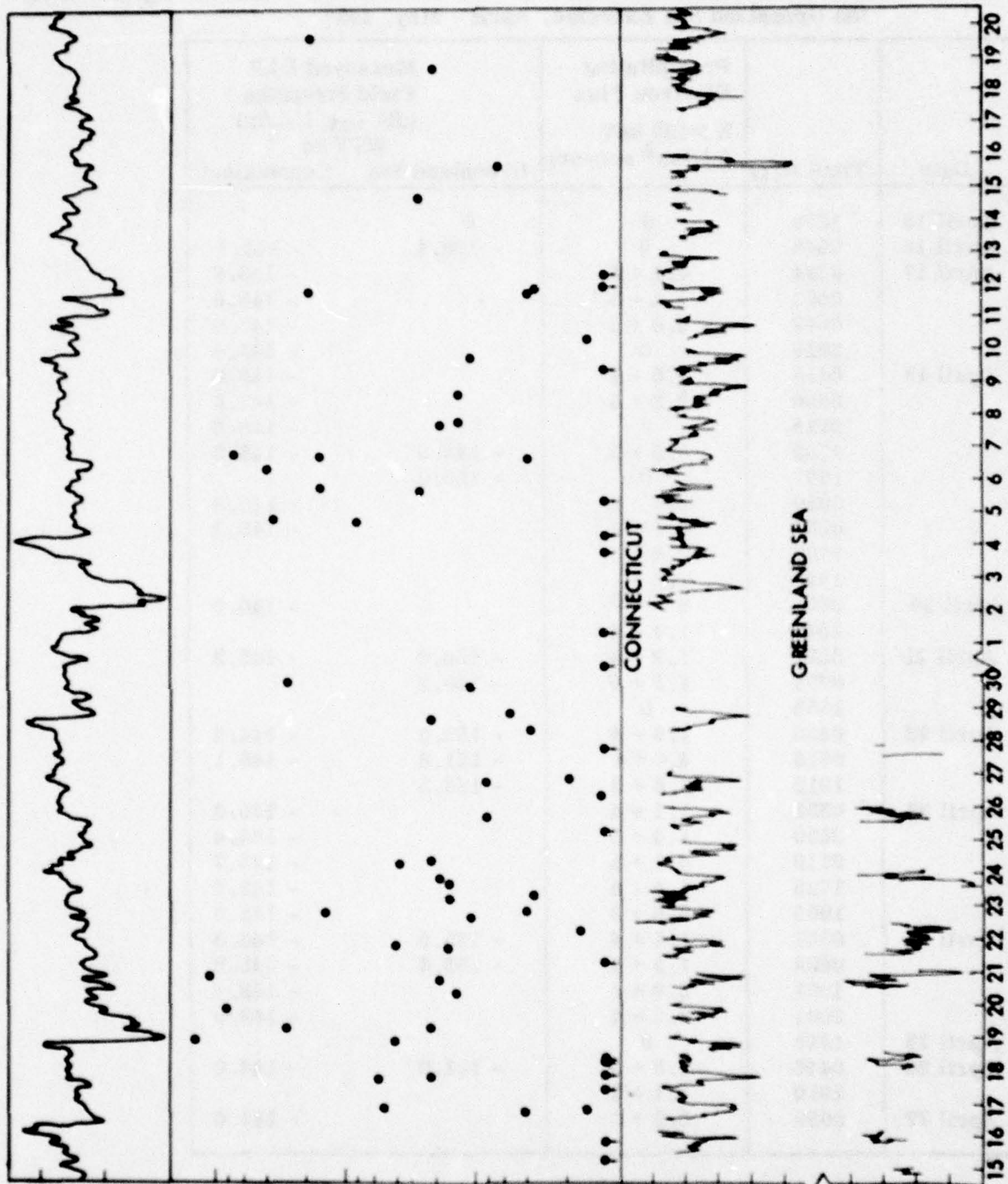

Figure 2-7 The ELF field strengths as measured in the Greenland Sea exercise and at the Connecticut receiving station. Also plotted are the fluxes of precipitating electrons >150 keV measured on the S72-1 satellite. The D_{st} geomagnetic index is plotted in the upper section.

Table 2-1 Measured Precipitating Electron Fluxes and ELF Signal Strengths During the Greenland Sea Exercise, April - May, 1977

Date	Time (UT)	Precipitating Electron Flux E >150 keV (el/cm^2 sec-sr)	Measured ELF Field Strengths (dB wrt 1 A/m) WTF to	
			Greenland Sea	Connecticut
April 15	1650	0	0	
April 16	0548	0	- 150.4	- 145.1
April 17	0324	4.1 + 3		- 145.6
	0503	1.4 + 3		- 146.6
	0642	5.0 + 4		- 146.6
	2016	0		- 143.4
April 18	0418	5.5 + 4		- 145.6
	0556	2.2 + 4		- 147.6
	0738	0		- 148.6
	1752	5.5 + 2	- 148.9	- 143.6
	1931	0	- 150.0	
	0650	1.4 + 6		- 145.3
	0837	4.1 + 4		- 145.3
	1708	2.8 + 5		
	1848	2.2 + 4		
April 20	0606	8.0 + 5		- 146.2
	1942	1.4 + 4		
April 21	0521	1.9 + 4	- 150.6	- 145.2
	0708	1.1 + 6	- 150.2	
	1855	0		
April 22	0436	1.6 + 4	- 152.0	- 144.0
	0616	4.0 + 4	- 151.8	- 146.1
	1812	1.6 + 3	- 153.3	
April 23	0352	1.1 + 4		- 145.0
	0530	1.4 + 5		- 144.4
	0710	4.1 + 3		- 145.7
	1728	1.6 + 4		- 142.0
	1906	3.6 + 3		- 142.6
April 24	0307	1.6 + 4	- 155.5	- 144.8
	0623	1.9 + 4	- 155.4	- 145.8
	1821	3.9 + 4		- 143.4
	2001	2.2 + 4		- 142.9
April 25	1916	0		
April 26	0445	8.3 + 3	- 151.0	- 144.0
	2010	1.1 + 3		
April 27	0550	8.3 + 3		- 144.6

Table 2-1 (Continued)

Date	Time (UT)	Precipitating Electron Flux E > 150 keV (el/cm^2 sec-sr)	Measured ELF Field Strengths (dB wrt 1 A/m) WTF to Greenland Sea	Connecticut
April 27	0731	1.9 + 3		- 147.3
April 28	0646	2.8 + 2		
	2020	3.9 + 3		- 143.2
April 29	0429	2.2 + 4		- 145.6
	0600	5.5 + 3		- 146.9
April 30	0336	1.1 + 4		
	0514	2.8 + 5		
	2028	0		
May 1	1944	0		
May 2	0523	2.0+ 6		
May 4	0547	0		- 144.7
	1909	0		
May 5	0449	8.3 + 4		- 145.4
	0629	3.6 + 5		- 143.4
	2003	0		- 142.9
May 6	0405	2.8 + 4		- 144.5
	0544	1.6 + 5		- 145.4
	1920	4.1 + 5		- 143.6
May 7	0320	4.1 + 3		- 145.1
	0459	1.6 + 5		- 145.6
	0638	7.2 + 5		- 145.6
May 8	0414	1.9 + 4		- 144.2
	0554	1.4 + 4		- 145.4
May 9	0329	1.4 + 4		- 146.2
	2022	0		- 143.8
May 10	0603	1.1 + 4		- 145.8
	1939	1.4 + 3		- 144.5
May 11	0431	4.1 + 3		- 146.6
	0612	3.6 + 3		- 148.3
	0755	0		- 145.8
	0938	1.9 + 5		- 144.6
	1945	0		- 143.6
May 15	0329	2.8 + 4		
May 16	0244	6.9 + 3		- 146.8
May 19	0348	2.2 + 4		- 144.3
May 20	0333	1.9 + 5		- 145.1

2.2 Search for Correlations Between Particle Fluxes and ELF Signal Strength

Several efforts were made to correlate the observed ELF signal strength with the fluxes of precipitating energetic electrons. One of the investigations is summarized in Figure 2-8, where the measured signal strengths are plotted as a function of the flux of precipitating electrons >150 keV measured at the same time. Under this investigation we are primarily concerned with nighttime measurements when the effects of energetic particle precipitation can best be studied, but both noon and midnight data have been used. In the presentation, the local noon flux measurements are plotted with solid symbols. With exclusion of either dayside or nightside data there is less scatter in the points, but even under such conditions, there is no evidence for a consistent variation between signal strength and electron flux. Similar conclusions followed from a search for correlation between the signal strength and the fluxes of much lower energy electrons in the energy range 0.6 - 1.5 keV. The data used in the latter study are presented in Figure 2-9.

Since the WTF transmitter is at a relatively low magnetic latitude, it is important to investigate whether there is any correlation between the measured signal strengths and the invariant latitude of the electron precipitation, particularly as related to the signal strengths received at Connecticut. With this consideration in mind, in Figure 2-10 the signal strengths measured at Connecticut and at Greenland are plotted as a function of the minimum invariant latitude of electron precipitation. Here again there is no evidence for a positive correlation.

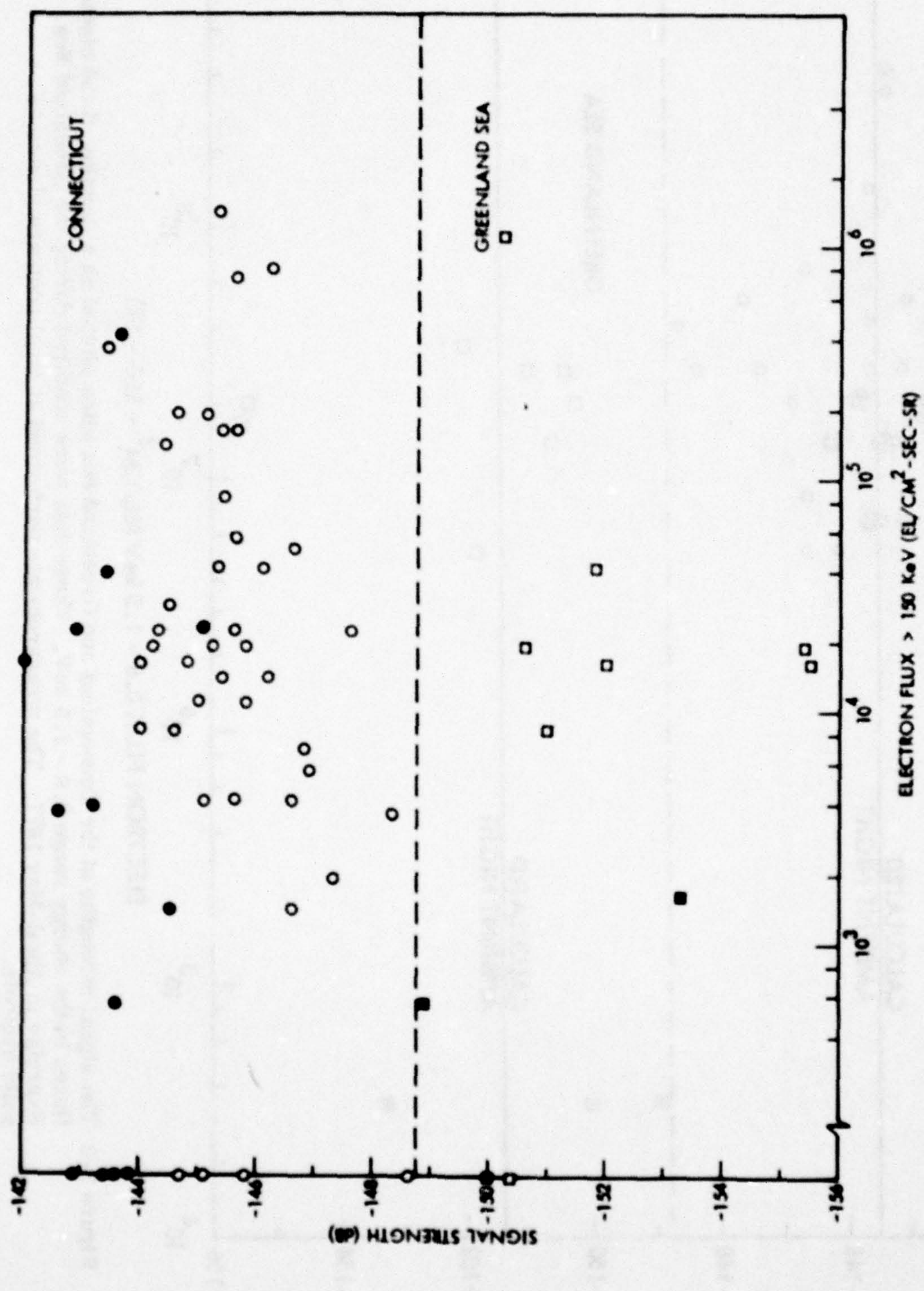

Figure 2-8 The ELF signal strengths at the Connecticut and Greenland Sea sites plotted as a function of the electron fluxes (>150 keV) measured from the S72-1 satellite. These data were acquired during the Greenland Sea Exercise in April - May 1977. The electron measurements performed at local noon are plotted as solid symbols.

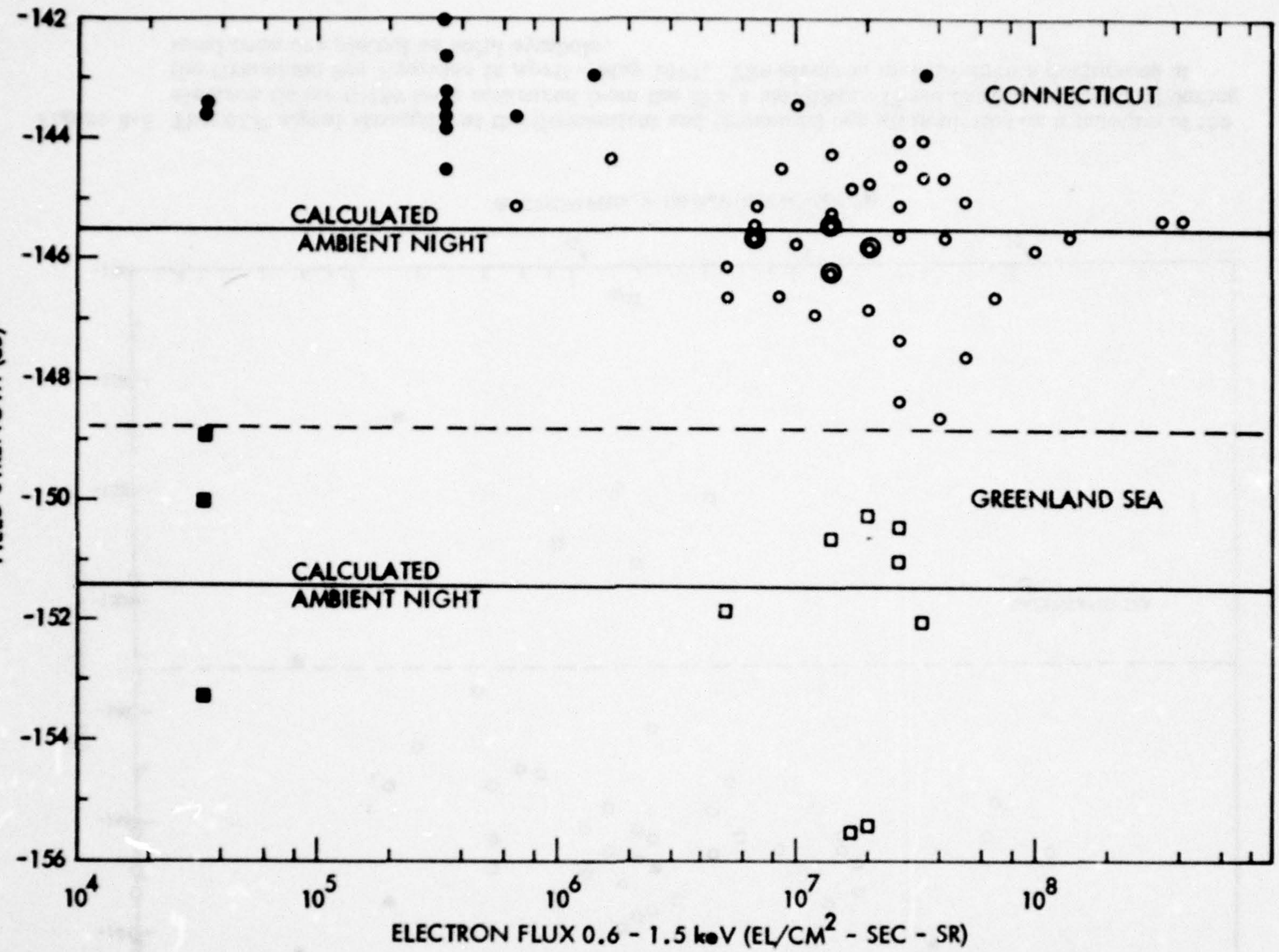

Figure 2-9 The signal strengths at the Connecticut and Greenland Sea sites plotted as a function of the electron fluxes in the energy range 0.6 - 1.5 keV. These data were acquired during the Greenland Sea Exercise in April-May 1977. The measurements performed at local noon are plotted as solid symbols.

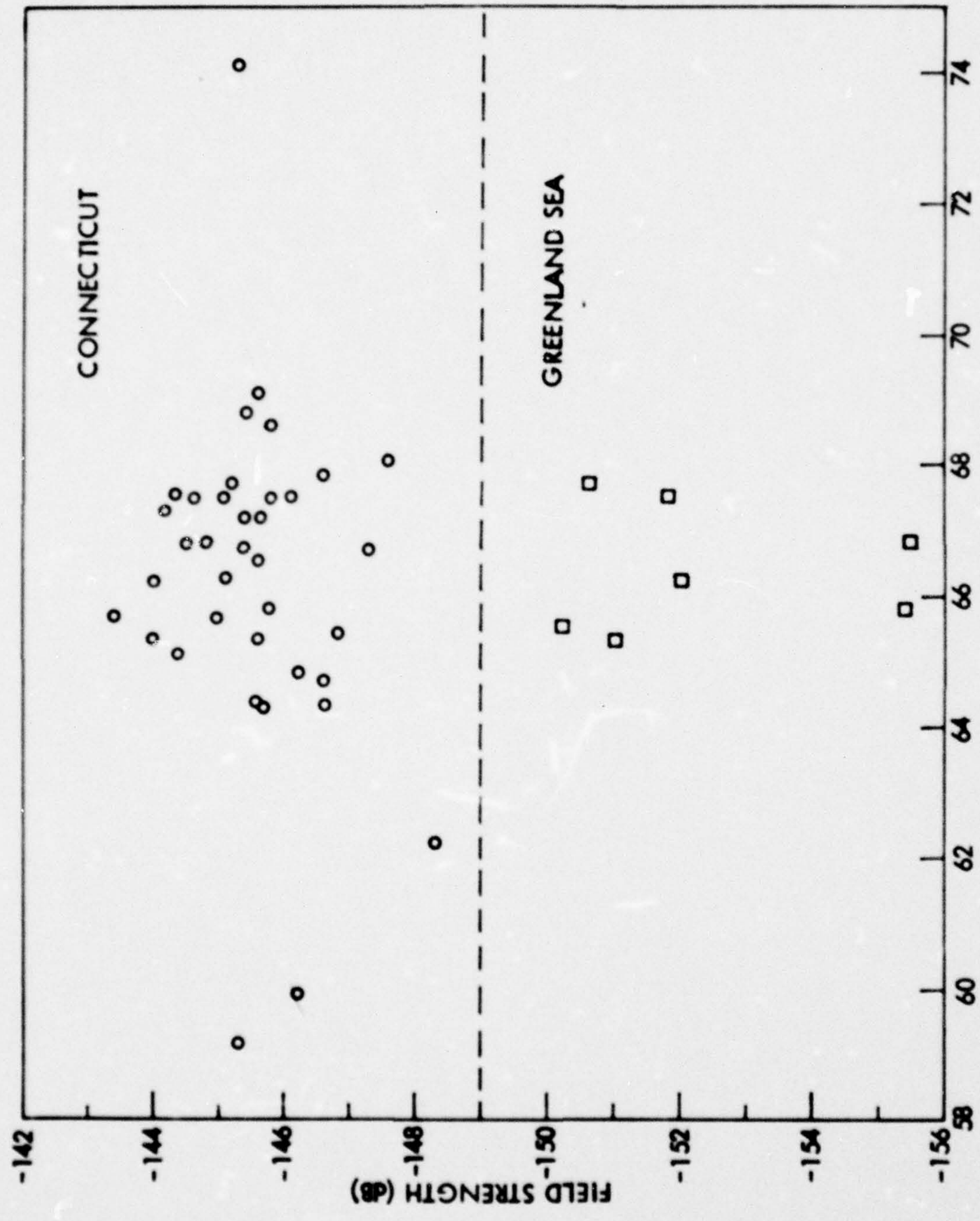

Figure 2-10 ELF signal strengths measured at the Connecticut and Greenland Sea sites as a function of minimum invariant latitude of electron precipitation. These data were measured during the Greenland Sea Exercise in April-May 1977.

Section 3
CALCULATIONS OF ELF PROPAGATION CHARACTERISTICS

3.1 Calculations for Propagation Path WTF to Connecticut and Greenland During 19 April and 7 May 1977 REP Events

For two of the major relativistic electron precipitation (REP) events observed in the April - May 1977 Greenland Sea exercise a more detailed analysis has been performed of the electron energy spectra and intensities and of the resulting energy deposition profiles. The inferred electron density contours are shown in Figure 3-1 along with one previously obtained during an intense relativistic electron precipitation event on 26 March 1976. It is clear that during the 19 April 1977 event the ionization produced at lower altitudes, ≤ 80 km, was much greater.

For each of the electron density profiles shown in Figure 3-1 calculations of the ELF signal strengths have been performed with the waveguide-mode computer program developed at the Naval Ocean Systems Center. The computations were performed with various path segmentations for the great-circle propagation to the receiving site at Tromso, Norway. For the calculations the electron precipitation intensities were assumed to be independent of longitude and to follow the known magnetic invariant latitude contours, as shown in Figure 3-2. The results are summarized in Table 3-1. For the relativistic electron precipitation events on 19 April 1977 and 7 May 1977, calculations were also made of the signal strengths at Thule and at Connecticut. These are provided in Tables 3-2 and 3-3.

From the results of the calculations for the electron precipitation events on 26 March 1976, 19 April 1977, and 7 May 1977, as well as other events, it is clear that either increases or decreases of signal may occur, depending upon the spatial extent and location of the ionization in relation to the transmitter and receiver. This complicated aspect of the signal transmission, coupled with the complex spatial distribution of electron precipitation events, emphasizes the need for future electron precipitation mapping techniques each as may be accomplished with bremsstrahlung x-ray spectrometers on a satellite. Although the predicted effects of a single relativistic electron precipitation event are not severe, due to their frequent occurrence they may provide the opportunity to verify experimentally the predicted effects of more severe and rarely occurring phenomena such as solar particle events.

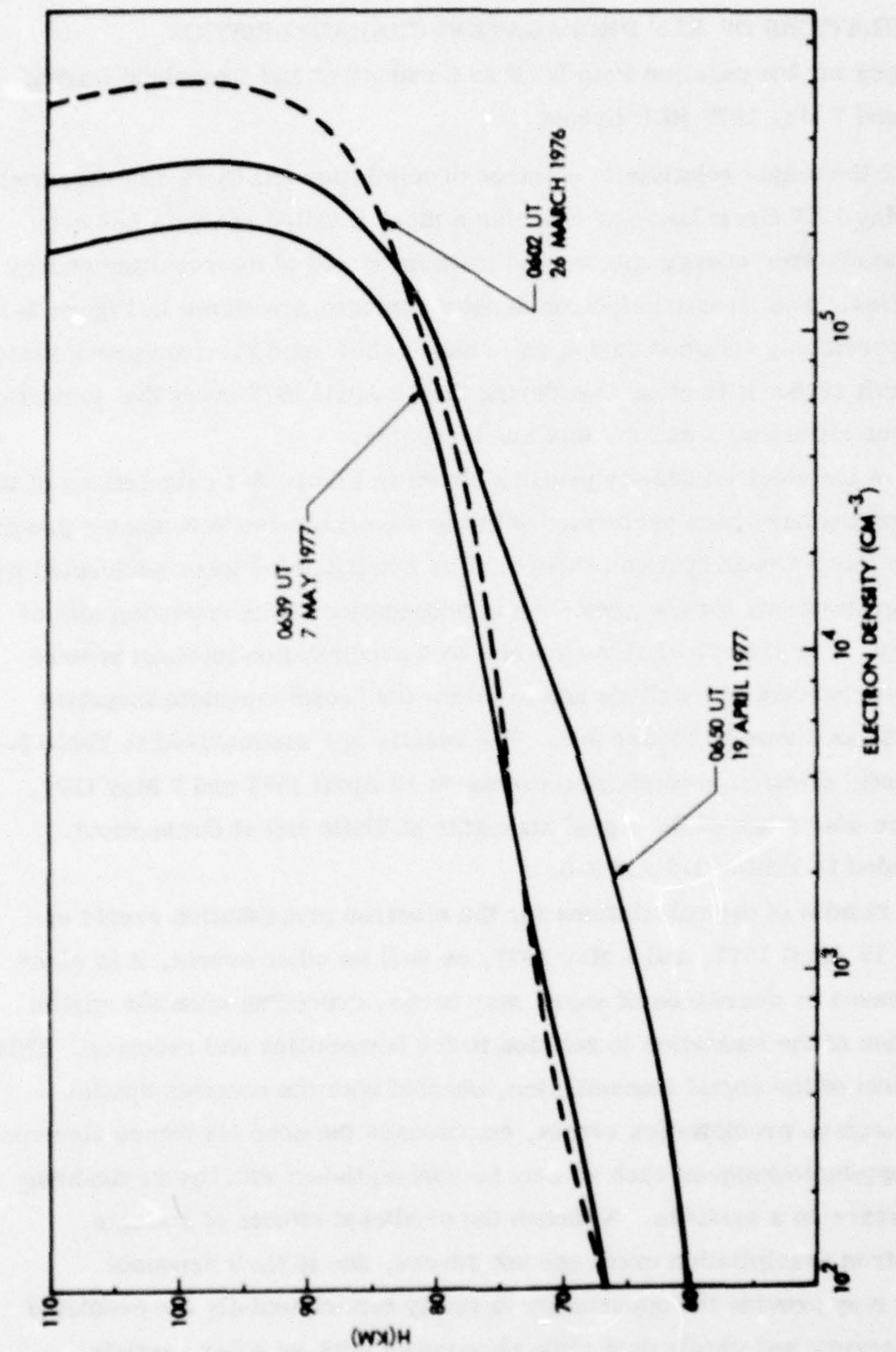

Figure 3-1 Electron density profiles inferred from the satellite measurements of precipitating electrons during 3 different events. Those of 19 April and 7 May were major REP events during the Greenland Sea exercise.

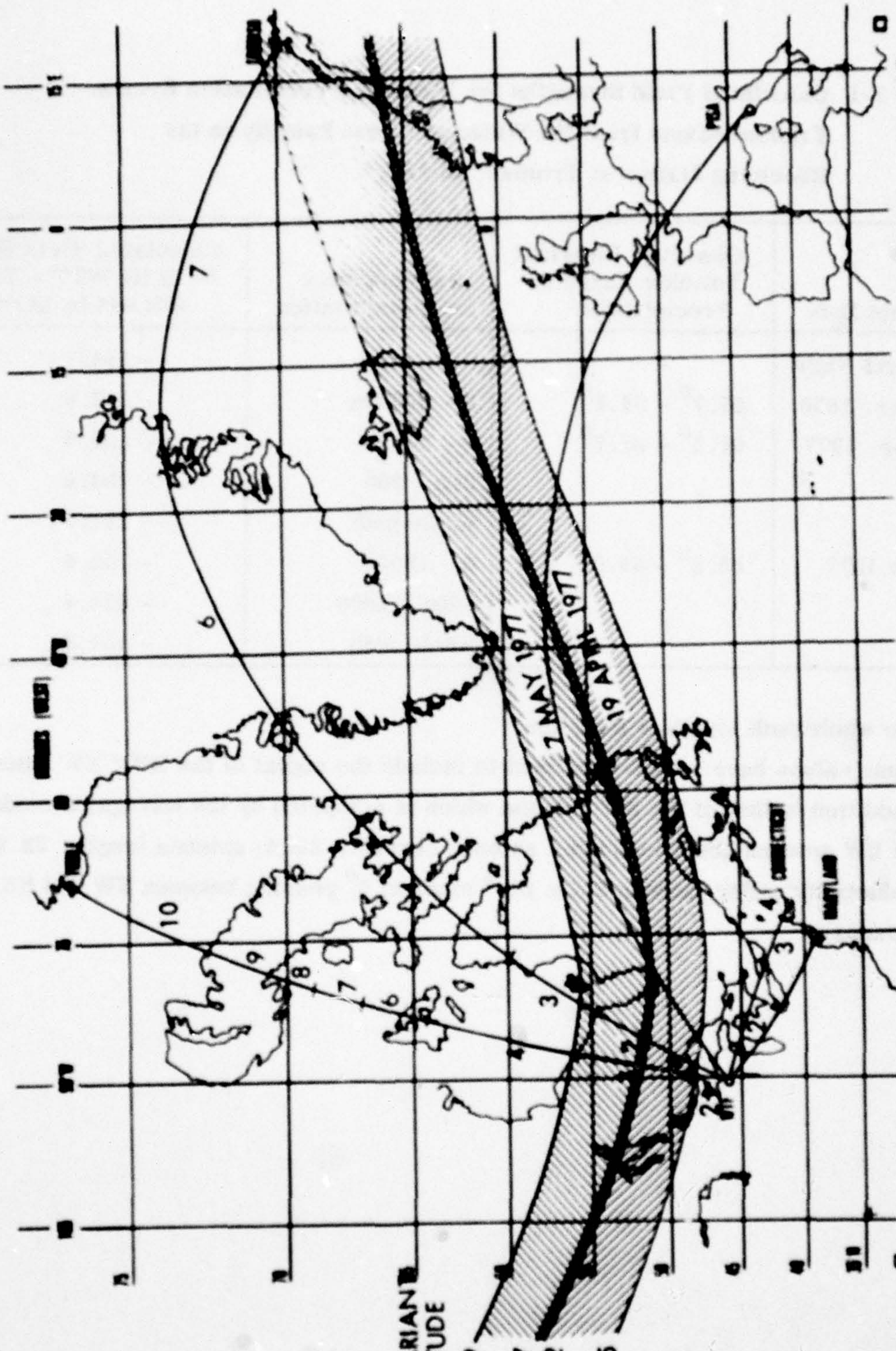

Figure 3-2 Plots of electron precipitation bands for the REP events of 19 April and 7 May 1977 during the Greenland Sea exercise. The bands are assumed to follow invariant magnetic latitude contours. Also shown are great circle paths from WTF to several ELF receiving stations with the segments used in ELF propagation calculations.

Table 3-1 Calculated Field Strengths for Electron Precipitation Events. Transmissions from the Wisconsin Test Facility to the Receiving Station at Tromso, Norway*

Event Date	Observed Invariant Latitude Range of Precipitation	Path Segment for Precipitation	Calculated Field Strength at 75 Hz WTF - Tromso† (dB wrt to 1A/m)
Ambient Night	-	-	- 154.7
26 Mar. 1976	57.7^{o} - 64.8^{o}	0 - 900 km	- 153.6
19 Apr. 1977	61.5^{o} - 65.7^{o}	0 - 900	- 153.5
		200 - 900	- 154.6
		whole path	- 151.9
7 May 1977	65.2^{o} - 68.9^{o}	0 - 1800	- 153.4
		1000 - 1800	- 154.4
		whole path	- 151.9

* The whole path length is 6000 km

† These values have been normalized to include the signal of the WTF EW antenna in addition to that of the NW antenna which is computed by the waveguide mode code. The EW antenna conditions are: antenna current: 300A; antenna length: 22.5 km; conductivity under antenna 3.2×10^{-4} mho/m; 0^{o} phasing between EW and NS antennas.

Table 3-2 Calculated Field Strengths WTF - Greenland* for 19 April and 7 May 1977 Precipitating Electron Profiles

Profile Date	Path Segments for Precipitation	Calculated Field Strength at 75 Hz (dB wrt 1 A/m)†	Calculated Change from Ambient Night (dB wrt 1 A/m)†
19 April	0 - 1200 km	- 152.1	+ 1.2
	300 - 1200 km	- 152.2	+ 0.1
7 May	0 - 1200 km	- 151.2	+ 1.1
	300 - 1200 km	- 152.1	+ 0.2
Ambient Night		- 152.3	

* Total path length 3500 km

† Normalized as indicated in Table 3-1

Table 3-3 Calculated Field Strengths WTF - Connecticut* for 19 April and 7 May 1977 Electron Profiles

Profile Date	Path Segments for Precipitation	Calculated Field Strength (75Hz) in dB wrt 1 A/m	Measured Field Strength in dB wrt 1A/m	Difference (DB)
19 April	0-1300 km	- 144.3	- 145.3	+ 1.0
	Whole Path	- 143.1		+ 2.2
7 May	0-1300 km	- 144.4	- 145.6	+ 1.2
	Whole Path	- 143.5		+ 2.1

* Whole path length was 1550 km

3.2 Calculations for the 26 March 1976 REP Event Over Several Propagation Paths With Better Account of Full Transmission Geometry

Calculations of the ELF signal strengths have been made with a better account of the full transmission geometry. The calculations were performed with position - dependent ionospheric electron and ion profiles for the satellite pass on 26 March 1976 during an electron precipitation event. During that event the satellite passed close to WTF at 0602 UT and the particle detectors recorded enhanced fluxes of precipitating electrons between ~ 41° and ~ 55°N geographic latitude. The fluxes were particularly strong between 45° and 50°N.

Two electron energy spectra were deduced for this pass, the data being averaged over:

a) $3.66 < L < 4.21$; - "hard" spectrum

b) $4.21 < L < 5.10$; - "soft" spectrum

From each of the electron energy spectra the ion-electron production rates in the atmosphere were calculated using the computer program AURORA (Walt, et al., 1968) as discussed in the earlier report (Imhof, et al., 1977). The electron density altitude profiles above 60 km were calculated using effective electron loss rates inferred from SPE measurements as described in that same report. In those events electron production rates and electron densities were high, comparable to those of this electron precipitation event. Electron densities at altitudes below 60 km at night are very small. Positive ion densities were assumed equal to electron densities at and above 80 km. At altitudes below 40 km, ambient N_+ profiles were used. In between these altitude limits a smooth fit interpolation was assumed.

Assuming that the electron precipitation occurs uniformly along the L-shells at all longitudes covered by the ELF paths under study (between 90°W and 20°E in longitude), these two sets of ionospheric profiles were applied to the various portions of the propagation paths as shown in Figure 3-3. Outside the areas of electron precipitation, the nighttime ambient electron and ion profiles were used. As an example, the path from WTF to Pisa was treated as follows:

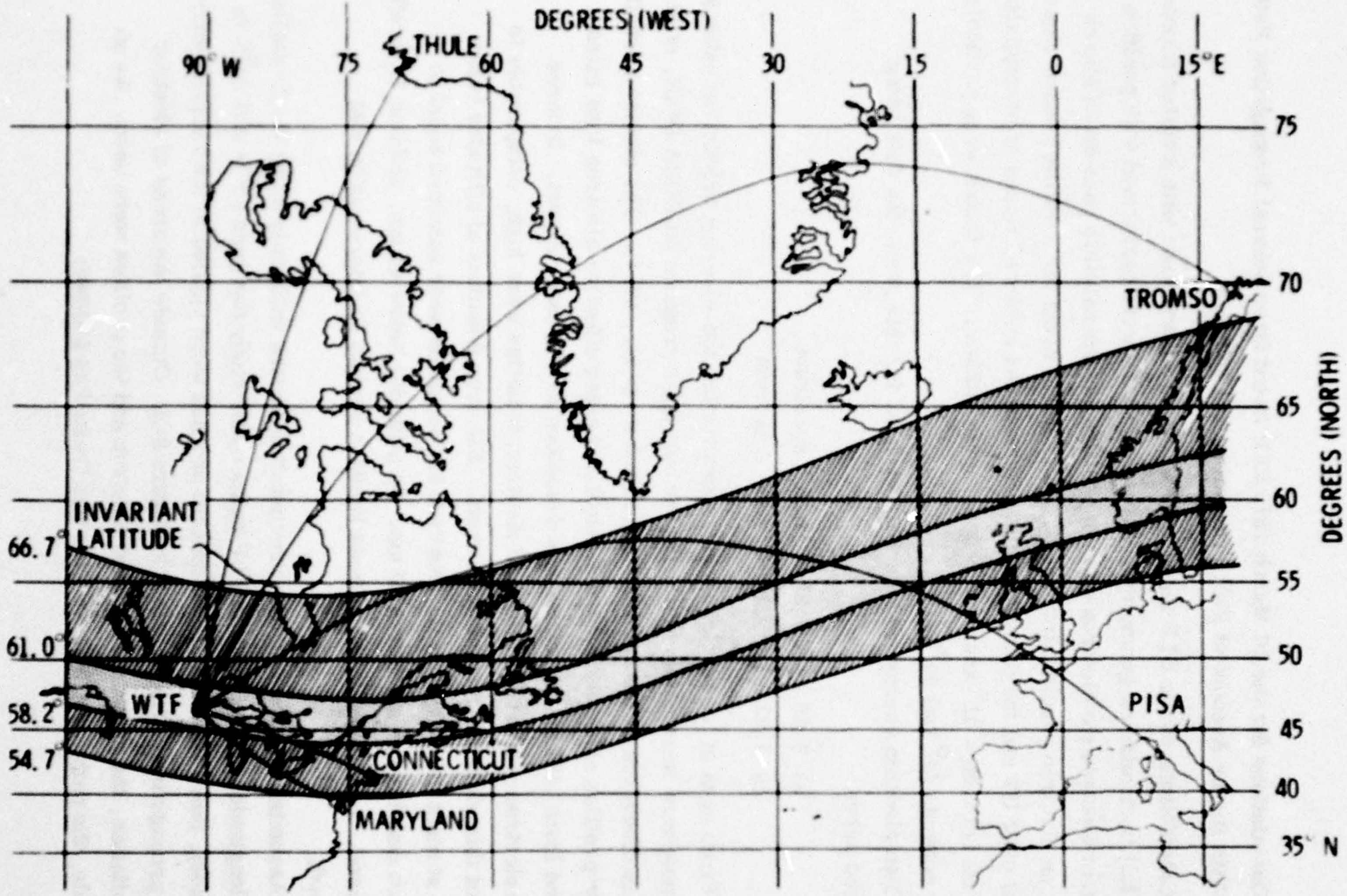

Figure 3-3 Schematic representation of the geometry used in calculation of the transmitted signal strengths for electron precipitation events at 0602 UT on 26 March 1976. At all longitudes the region of most intense electron precipitation is assumed to span the central invariant latitude interval 58.2° to 61.0°. The regions of weaker electron precipitation cover the intervals 54.7° to 58.2° and 61.0° to 66.7° invariant latitude.

Distance from WTF	N_e, N_+ Profiles for:
0 - 200 km	"hard" spectrum
300 - 3900 km	"soft" spectrum
4000 - 4900 km	"hard" spectrum
5000 - 5500 km	"soft" spectrum
5600 - 7500 km	ambient conditions

The results are presented in Table 3-4 which compares the predicted normalized field strengths at 75 Hz with the ambient nighttime field strength for five ELF recording stations. The fifth column gives the predicted change of field strength (in dB) during the event. It is noted that signal increases of 0.6 dB to 1.9 dB were predicted for the various stations using this procedure.

In Table 3-5 we show the predicted and measured absolute field strengths. The last column shows the actually measured signal changes (between 0.0 and + 3.2 dB). The predicted changes for the three longest paths were all of the right sense, but complete numerical agreement was not obtained. However, taking into account the uncertainties involved the results are regarded as showing satisfactory agreement. There is very good agreement between predictions and measurements at Maryland, fair agreement at Tromso, whereas for Thule and Pisa the results are less satisfying. The measured signal strength at Thule averaged over a three hour interval around 0600 UT is within 0.2 dB of the measured value for Norway. Since the latter path is 2.4 Mm longer than the path to Thule, it is quite obvious that the Thule path is experiencing nonambient conditions also outside the precipitation region indicated in Figure 3-3. This finding stresses the need for more complete information about the conditions all along the propagation path in order to make good signal strength predictions.

The agreement between the predicted and measured absolute field levels at Pisa, Italy is also poorer than desired. When correction is made for adding the E-W antenna contribution to the N-S antenna signal calculated by the waveguide mode code the factor is the rather large value + 4.8 dB. This correction is much larger than the corrections for the other ELF sites and any uncertainty in this value will, of course, have a relatively larger effect on the absolute values for Pisa. Another

explanation is that the ambient nighttime conditions used may not be applicable to the southernmost portion of the path to Pisa.

Table 3-4 Calculated ELF Field Strengths For the REP Event of 26 March 1976

Receiving Station	Segment for Precipitation	Calculated Field Strengths at 75 Hz in dB wrt 1 A/m*		
		Ambient Night	During Event	Predicted Change
Connecticut, USA		- 145.2	- 143.3	+ 1.9
Maryland, USA	See	- 147.9	- 147.3	+ 0.6
Thule, Greenland	Figure 3-3	- 151.3	- 151.3	+ 1.0
Tromso, Norway		- 154.7	- 153.6	+ 1.1
Pisa, Italy		- 154.0	- 152.3	+ 1.7

* Normalized as indicated in Table 3-1.

Table 3-5 Comparison of Predicted and Measured ELF Field Strengths for the REP Event of 26 March 1976

	ELF Field Strengths at 75 Hz during event*		Change in Field Strength during event	
	Predicted (dB wrt 1 A/m)	Measured (dB wrt 1 A/m)	Predicted (dB)	Measured (dB)
Connecticut, USA	- 143.3	no meas.	+ 1.9	no meas.
Maryland, USA	- 147.3	- 147.2	+ 0.6	0.0
Thule, Greenland	- 151.3	- 155.0	+ 1.0	+ 0.5
Tromso, Norway	- 153.6	- 155.2	+ 1.1	+ 2.0
Pisa, Italy	- 152.3	- 154.7	+ 1.7	+ 3.2

* Normalized as indicated in Table 3-1

3.3 Calculations for Hypothesized SPE Profiles

An earlier report (Imhof, et al., 1977) included results of some calculations for typical SPE electron and ion density altitude profiles applied to the path WTF to Tromso, Norway. The main conclusions of those calculations were: 1) typical SPE nighttime conditions from the August, 1972 event will decrease ELF signal strength at 75 Hz by several dB for uniform conditions all over the path; 2) the received ELF field strength in Norway was predicted to be reduced by an additional 1 - 3 dB when the WTF transmitter area was outside the SPE disturbed region; 3) the ELF signal strength was especially sensitive to changes in the positive ion density altitude profile below 45 - 50 km.

In the present report, we present some additional results of ELF calculations for SPE conditions including for the first time results for daytime propagation conditions.

3.3.1 Daytime Conditions

For the daytime ionospheric conditions we have taken the results obtained in an earlier study (Reagan, 1975; Gunton, Meyerott and Reagan, 1977; Gunton, private communication, 1978). The electron and ion densities and ion pair production rates are listed in Table 3-6 and their profiles are shown in Figure 3-4. The data refer to the SPE of August 1972 at 1508 UT on 4 August, near the peak of this unusually intense event. The local time at Chatanika, Alaska, where the data were obtained, was 0508 LT, corresponding to a solar zenith angle of $\chi = 79.5^{o}$. The peak ionization rate occurred at approximately 40 km with 4.5×10^{4} ion pairs/cm^{3}-sec. The electron density profile was measured between 90 and 55 km (Reagan, 1975). Values at lower altitudes were predicted using the chemistry code of Gunton, et al., (1977). The values for the positive ions between 80 and 40 km are likewise obtained using the same chemistry code. At lower altitudes the values for the posivive ion density N_+ are obtained using the formula

$$N_+ = \sqrt{q/\alpha_i(h,T)}$$

where height and temperature dependent values of the ion-ion recombination rate α_i are used, cf. Table 3-7. These values of N_+ are labeled "original profile" in Figure 3-4.

Table 3-6 Electron and Ion Density Profiles for 4 August 1972 1508 UT of Chatanika, Alaska Together With the Calculated Ion Pair Production Rates From the Precipitating Protons

Altitude (km)	Electron Density (cm^{-3})	Positive Ion Density (cm^{-3})	Production Rate (ion pairs/cm^3-sec)
100	5.0 10^{5}	5.0 10^{5}	1.91 10^{2}
95	1.0 10^{5}	1.0 10^{5}	4.86 10^{2}
90	6.5 10^{4}	6.5 10^{4}	1.06 10^{3}
85	4.8 10^{4}	4.8 10^{4}	1.99 10^{3}
80	3.8 10^{4}	3.8 10^{4}	3.21 10^{3}
75	5.0 10^{4}	5.0 10^{4}	5.16 10^{3}
70	5.5 10^{4}	7.0 10^{4}	8.17 10^{3}
65	5.0 10^{4}	1.4 10^{5}	1.24 10^{4}
60	3.6 10^{4}	2.5 10^{5}	1.79 10^{4}
55	2.0 10^{4}	3.7 10^{5}	2.46 10^{4}
50	1.0 10^{4}	5.0 10^{5}	3.25 10^{4}
45	1.1 10^{3}	6.0 10^{5}	4.03 10^{4}
40	2.15 10^{2}	6.0 10^{5}	4.47 10^{4}
35	1.0 10^{1}	5.4 10^{5}	3.91 10^{4}
30	Ambient	3.7 10^{5}	1.89 10^{4}
25		1.15 10^{5}	3.74 10^{3}
20		2.05 10^{4}	2.17 10^{2}
15		Ambient	
10			

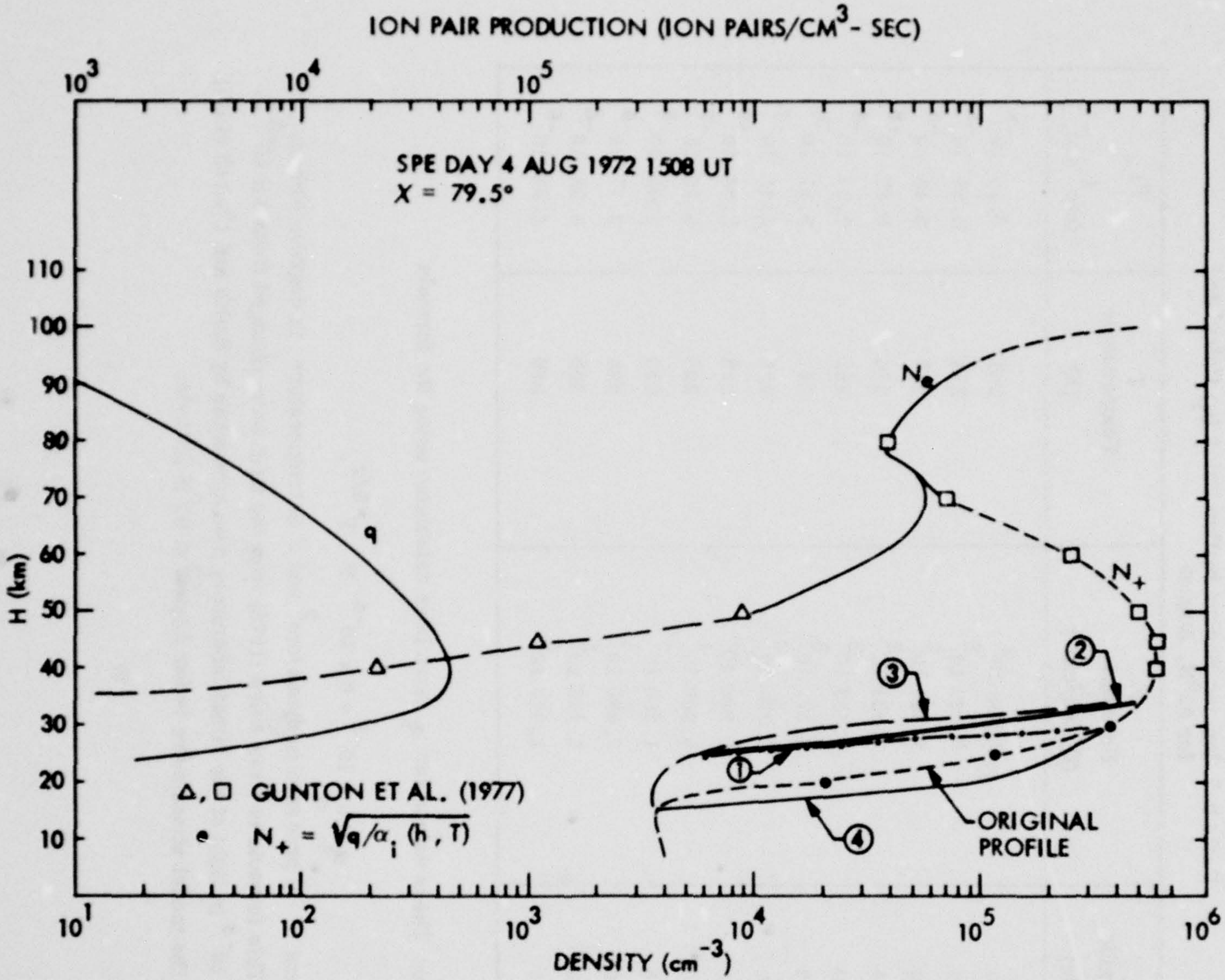

Figure 3-4 Profiles of electron and positive ion densities representing the SPE of 4 August 1972 at 1508 UT. The four curves labeled (1) - (4) are variations of the original N_+ profile below 35 km used to find the sensitivity of ELF propagation to N_+ profile variations.

Table 3-7 Ion-ion Recombination Rates (α_i) Calculated for 65°N, August

Altitude (km)	P Pressure (Dynes/cm^2)	T Temperature (K)	α_i (cm^3 sec^{-1})
60	$2.869 \; 10^2$	261	$5.16 \; 10^{-8}$
55	$5.366 \; 10^2$	274	$5.26 \; 10^{-8}$
50	$9.834 \; 10^2$	278	$5.46 \; 10^{-8}$
45	$1.801 \; 10^3$	274	$5.87 \; 10^{-8}$
40	$3.383 \; 10^3$	261	$6.84 \; 10^{-8}$
35	$6.571 \; 10^3$	247	$9.11 \; 10^{-8}$
30	$1.305 \; 10^4$	236	$1.41 \; 10^{-7}$
25	$2.800 \; 10^4$	228	$2.64 \; 10^{-7}$
20	$5.900 \; 10^4$	225	$5.16 \; 10^{-7}$
15	$1.260 \; 10^5$	225	$1.05 \; 10^{-6}$
10	$2.680 \; 10^5$	225	$2.17 \; 10^{-6}$
5	$5.410 \; 10^5$	260	$3.03 \; 10^{-6}$
0	$1.017 \; 10^6$	289	$4.35 \; 10^{-6}$

Note: These values for α_i have been calculated using the formula

$$\alpha_i = 5 \times 10^{-8} + 6 \times 10^{-6} \; P \; T^{-5/2},$$

where P is pressure in dynes/cm^2 and T is temperature in degrees Kelvin.

This formula is from Niles (1976) with the first term changed from 3×10^{-8} to 5×10^{-8} in light of the latest laboratory measurements by Smith and Church (1977).

The model atmosphere is for August at 65°N latitude.

The propagation characteristics at 75 Hz for the path segments from WTF to Tromso are given in Table 3-8. The resulting attenuations are shown in Table 3-9. It may be noted that the attenuations for SPE daytime conditions (4 August 1972, 1508 UT) are greater than previously calculated for ambient nighttime conditions (Imhof, et al., 1977) by 3.3 dB when the WTF transmitter is inside the SPE region and by 6.7 dB when it is outside. Also, as shown in Table 3-9, such daytime SPE conditions are expected to cause ELF signal attenuation to be the same as the values calculated earlier for SPE nighttime conditions (Imhof, et al., 1977) with the WTF transmitter inside the SPE region, and to be larger by 0.8 dB with the transmitter outside.

Table 3-8 Propagation Characteristics at 75 Hz Calculated for the WTF to Norway Path for Daytime SPE Conditions (4 Aug. 72 1508 UT)

Range from WTF (km)	Path Segment	Attenuation rate α (dB/Mm)	Relative Phase Velocity v/c	Excitation Factor (dB)
0-200	WTF	2.62	0.74	3.21
200-1000	Canada	2.51	0.74	3.13
1000-1800	Hudson Bay	2.37	0.75	3.02
1800-2900	North Canada	2.51	0.74	3.13
2900-3300	Davis Strait	2.37	0.75	3.02
3300-4400	Greenland	3.72	0.70	4.05
4400-5800	Norwegian Sea	2.37	0.75	3.02
5800-6000	Tromso Area	2.51	0.74	3.13

Table 3-9 Calculated Field Strengths for Transmission From the Wisconsin Test Facility to Tromso, Norway

	Calculated Field Strength at 75 Hz* (dB wrt 1A/m)
Ambient Nighttime †	-154.7
SPE Daytime Conditions	
4 Aug. 1972, 1508 UT ($\chi = 79.5^{\circ}$)	
WTF Inside SPE Region	-158.0
WTR Outside SPE Region	-161.4
SPE Nighttime Conditions †	
4 Aug. 1972, 1144 UT ($\chi = 95.3^{\circ}$)	
WTF Inside SPE Region	-158.0
WTF Outside SPE Region	-160.6

* Normalized as indicated in Table 3-1

† See Imhof, et al., (1977)

Some numerical tests have been made to explore the sensitivity of the ELF field strength calculations during solar particle events to changes in the ion and electron density profiles at altitudes below 60 km. Some examples are presented for daytime and nighttime SPE conditions.

The first case is based on SPE conditions on 4 August 1972 at 1508 UT shown in Figure 3-4. ELF field strength calculations have been made for four modifications of the N_+ profile in the altitude regime 35 - 15 km as shown in Figure 3-4. In this altitude regime ions completely dominate over the electron contribution to the conductivity. The calculated field strengths are given in Table 3-10, and the propagation characteristics are shown in Table 3-11.

Table 3-10 ELF field strengths for propagation over the path from WTF to Tromso resulting from changes in the positive ion profile at low altitudes (Figure 3-4)

Profile	Changes in N_+ in Altitude Region	ELF Field Strength at 75 Hz* (dB wrt 1A/m)
Original	None	-158.0
1	30-15 km	-156.7
2	35-15 km	-155.0
3	35-15 km	-153.6
4	30-15 km	-158.9
Ambient Night		-154.7

* Normalized as indicated in Table 3-1

Table 3-11 Propagation Characteristics for SPE Daytime Conditions, 4 Aug. 1972 at 1508 UT for Various Profiles at Low Altitudes

Range From WTF	Attenuation Rate (dB/Mm)					Relative Phase Velocity v/c					Excitation Factor (dB)				
	ORIG	1	2	3	4	ORIG	1	2	3	4	ORIG	1	2	3	4
0–200	2.63	2.41	2.09	1.84	2.77	0.74	0.74	0.75	0.75	0.74	3.21	3.20	2.67	2.50	3.24
200–1000	2.51	2.30	1.98	1.73	2.66	0.74	0.74	0.75	0.75	0.74	3.13	3.11	2.60	2.41	3.15
1000–1800	2.37	2.16	1.83	1.60	2.51	0.75	0.75	0.76	0.76	0.75	3.02	3.01	2.50	2.31	3.04
1800–2900	2.51	2.29	1.98	1.73	2.66	0.74	0.74	0.75	0.75	0.74	3.13	3.11	2.60	2.41	3.15
2900–3300	2.37	2.15	1.84	1.60	2.51	0.75	0.75	0.76	0.76	0.75	3.02	3.01	2.50	2.31	3.04
3300–4400	3.72	3.49	3.14	2.87	3.89	0.70	0.69	0.70	0.70	0.70	4.05	4.04	3.53	3.34	4.08
4400–5800	3.37	2.15	1.84	1.60	2.51	0.75	0.75	0.76	0.76	0.75	3.02	3.01	2.50	2.31	3.04
5800–6000	2.51	2.29	1.98	1.73	2.65	0.74	0.74	0.75	0.75	0.74	3.13	3.11	2.60	2.41	3.15

This investigation has indicated the major effort a solar particle event may have on ELF signal propagation. Under daytime SPE conditions, it was found that the signal attenuations are slightly larger than for the same SPE input under nighttime conditions, illustrating the importance of the solar zenith angle parameter. The ELF field strengths are also found to be very sensitive to details of the positive ion density profile below 35 km. As a consequence of the latter finding, it is clearly important to take accurate account of the ion pair production by the high energy tail of the solar proton spectrum which produces ionization at low altitudes.

3.3.2 Variation in Electron Profile

The electron and ion profiles used in our earlier study (Imhof, et al., 1977) of ELF propagation during nighttime SPE conditions, those of 4 August 1972 at 1144 UT ($\chi = 95.3^{\circ}$), are shown in Figure 3-5. The original profile gave a calculated ELF signal strengths, WTF to Tromso of -157.7 dB wrt 1 A/m normalized as indicated in Table 3-1. Changing the electron density below 55 km according to Figure 3-5, the signal strength was the slightly higher value - 156.6 dB wrt 1A/m. Analysis of this result showed that the increased electron densities around 40 - 50 km led to lower attenuation rates for the various path segments by about 0.14 to 0.16 dB/Mm and increases in the excitation factor by 0.20 to 0.22 dB adding up to a 1.1 dB increase in signal strength.

3.3.3 Variations in Ion Profile

SPE conditions at Chatanika on 5 August 1972 1254 UT ($\chi = 91.4^{\circ}$) are shown in Figure 3-6. Electron densities above ~60 km are measured values and below ~60 km are ~2 orders of magnitude smaller than the calculated ion densities. A little below 60 km the ion conductivities dominate over electron effects. Ion densities at and above 60 km, marked by squares were computed with the code developed by Gunton, et al. (1977). From 60 km down to 30 km positive ion profiles 1 through 3 were calculated using the relation $N_+ = \sqrt{q/\alpha_i}$ where q is the ion production rate and α_i is the ion neutralization rate. For profile 1, an older "incorrect" α_i profile was used. This result does however serve to illustrate the importance of positive ions. Profile 2 was calculated using a constant value

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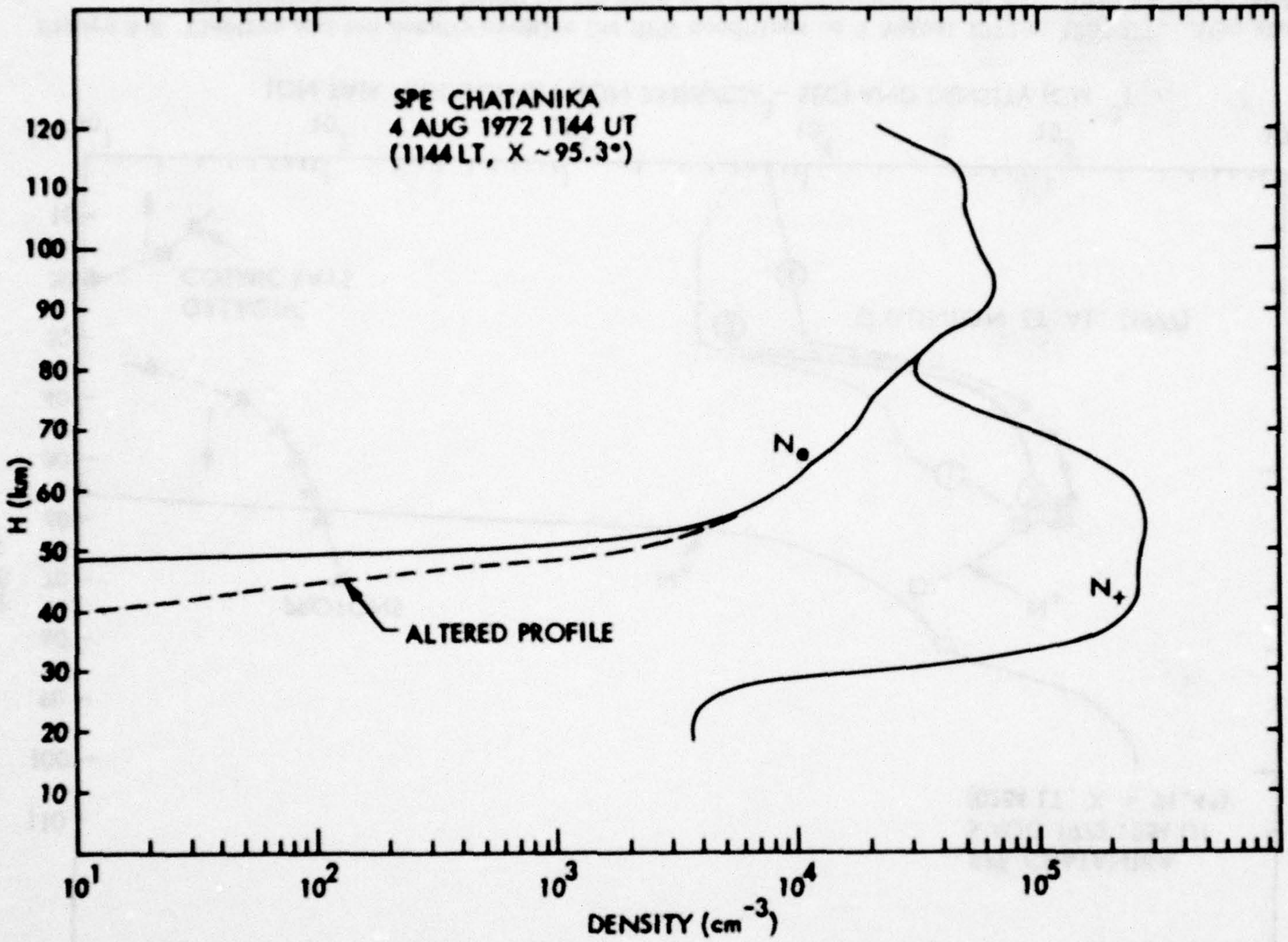

Figure 3-5 Electron and ion density profiles from Imhof, et al. (1977) for the SPE on 4 August 1972 at 1144 UT, solar zenith angle $\chi = 95.3^o$. The altered profile is used to find the sensitivity of ELF propagation to an electron density change.

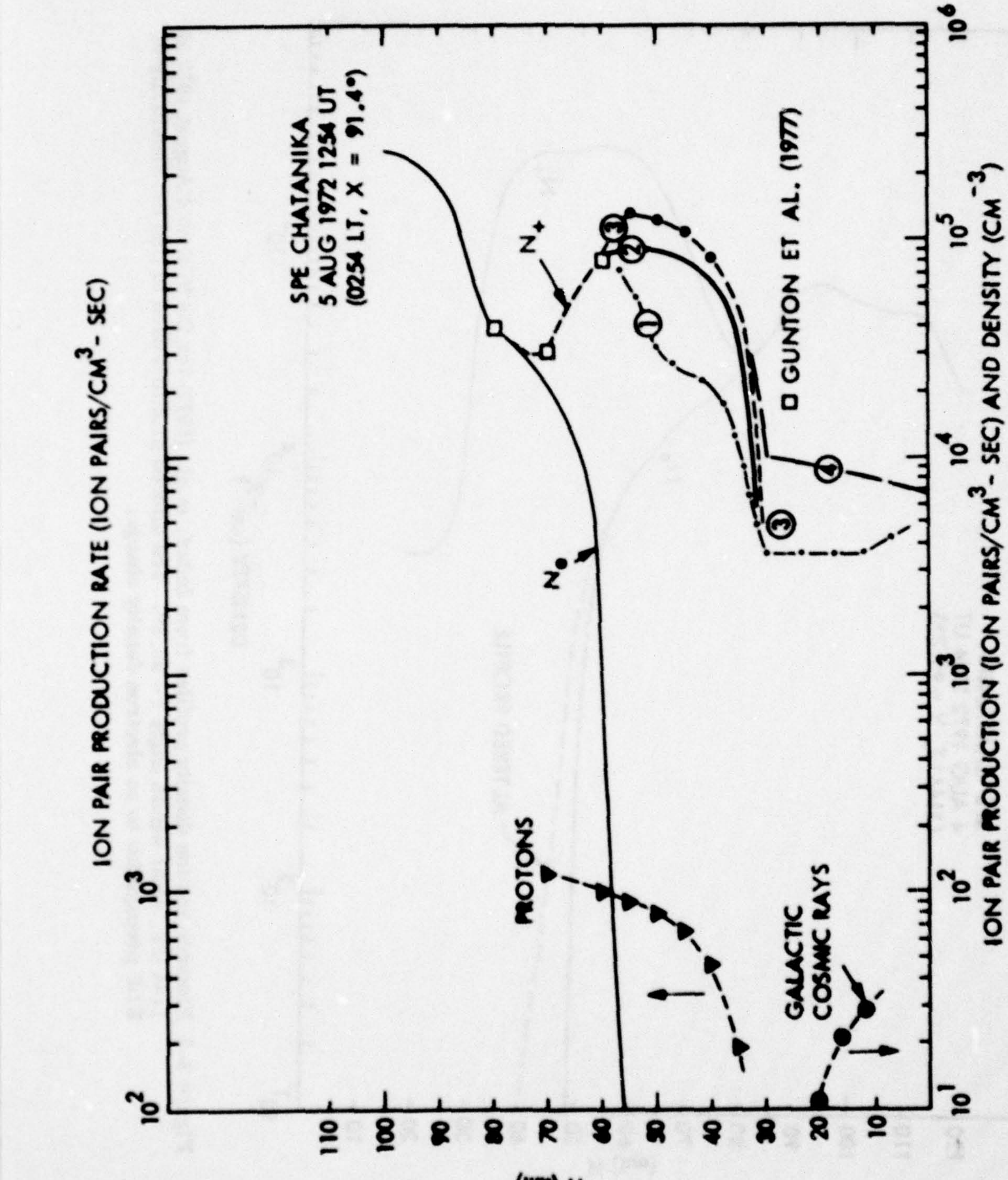

Figure 3-6 Electron and ion density profiles for SPE conditions on 5 August 1972 at 1254 UT. Also shown are several N_+ curves below 60 km used in a study of sensitivity of ELF propagation to positive ion density.

$\alpha_i = 1. \times 10^{-7}\ cm^3\ sec^{-1}$ and profile 3 was calculated using the α_i profile of Table 3-7 presently thought to best represent the laboratory measurements of α_i for atmospheric ions. The positive ion densities in profile 3 below ~30 km are typical ambient nighttime densities. The results of these calculations are summarized in Table 3-12.

The large change in signal strength (2.2 dB) between profile 1 and profile 2 shows the importance of ion densities in the 60 - 30 km region when electron densities are low there. Profile 4 is nearly identical to profile 3 down to about 30 km but exhibits larger values below 30 km. The very small difference in signal strength, 0.1 dB, between the two indicates that the region below 30 km is relatively unimportant for propagation at 75 Hz, unless it is ionized well above ambient conditions as was the case in Figure 3-4 above.

Table 3-12 ELF Field Strengths for Propagation from WTF to Tromso Resulting From Changes in the Positive Ion Profile Below 60 km

N_+ Profile	α_i Profile 60 - 30 km	Signal Strength at 75 Hz* (dB wrt 1 A/m)
1	"incorrect"	- 154.6
2	$\alpha_i = 1. \times 10^{-7} cm^3 sec^{-1}$	- 156.8
3	α_i from Table 3-7	- 156.8
4	like 3, but N_+ larger below 30 km	- 156.9

* Normalized as indicated in Table 3-1

Section 4
IMPACT OF IMPORTANT CHEMISTRY PARAMETERS ON ELF PROPAGATION

4.1 Importance of Solar Zenith Angle

At any one time, e.g., 1200 UT, the local time at each point along an ELF transmission path is different, and hence the solar zenith angle (χ) is different. Since electron and ion densities depend on the solar zenith angle, it is necessary in a complete treatment to take solar zenith angle variation into account. Some calculations have been made for a path from WTF to Tromso, Norway using hypothesized profiles to represent conditions on 31 March at 2100 UT. These conditions are shown in Table 4-1.

The season and time have been chosen so that data from the August 1972 SPE at solar zenith angles of 95.3° and 79.5° could be matched fairly well to average solar zenith angles of some of the eight segments of the WTF-Tromso path (see Table 4-2). The calculations of electron density profiles were made using the ion pair production rates of the 4 August 1972 event at 1144 UT (Reagan, et al., 1978b) for both $\chi = 95.3^{\circ}$ and $\chi = 79.5^{\circ}$. However, the electron loss rates were derived from measurements of the event (Reagan and Watt, 1976) at two times: 1144 UT on 4 August for $\chi = 95.3^{\circ}$ and 1508 UT on 4 August for $\chi = 79.5^{\circ}$. Electron density profiles were calculated using $N_e = \sqrt{q/\Upsilon_e}$ where q is the production rate and Υ_e is the effective electron loss rate. Electron densities needed at $\chi = 89.5^{\circ}$ for one segment of the path were obtained by interpolation between the results for $\chi = 95.3^{\circ}$ and 79.5°.

Since the transmitter at WTF as well as the first half of the path are in darkness, a profile for night, not derivable from the 4 August 1972 SPE data, was needed. Electron loss rates Υ_e were taken from data given by Imhof, et al., (1977) for nighttime conditions. The ion pair production rates also were those of 1144 UT on 4 August 1972. The resulting electron density altitude profiles are shown in Figure 4-1.

The positive ion density profile in Figure 4-1 was calculated at 80, 70, and 60 km using the chemistry code of Gunton, et al., (1977). Densities below 60 km were approximated using the relation $N_+ = \sqrt{q/\alpha_i}$ where the ion production rates were those of Reagan, et al., (1978b) and α_i was given the constant value

Table 4-1 Approximate Conditions Along the Transmission Path From WTF to Tromso on 21 March at 2200 UT

Segment	Range from WTF (km)	Latitude North	Longitude East	Solar Zenith Angle
1	0 - 200	48°	271°	68.5°
2	200 - 1000	52°	274°	72°
3	1000 - 1800	57°	279°	77°
4	1800 - 2900	64°	290°	83°
5	2900 - 3300	68°	302°	89.5°
6	3300 - 4400	71°	318°	94°
7	4400 - 5800	72°	355°	104°
8	5800 - 6000	69°	18°	110°

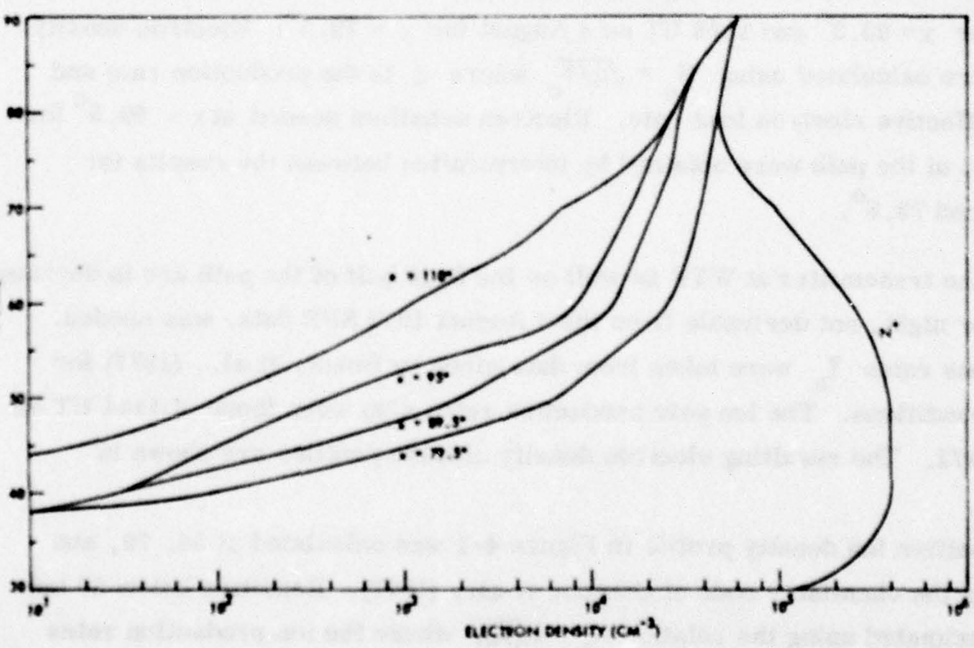

Figure 4-1 Electron density profiles for the 4 August 1972 (1144 UT) solar particle event at the four indicated solar zenith angles. The positive ion density, taken to be independent of solar zenith angle, is also shown.

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$1 \times 10^{-7} cm^3 sec^{-1}$. The positive ion density profile was arbitrarily held constant over the path in order that the effect of variation of electron density profiles only might be determined.

An initial calculation was made in which the first four segments were assigned the electron density profile for day ($\chi = 79.5^o$). Segments 5 and 6 were assigned profiles for $\chi = 89.5^o$ and $\chi = 95^o$, respectively. Segments 7 and 8 were given the profile corresponding to $\chi = 110^o$. The results are shown in Table 4-2. When the attenuation over the path was calculated, the result was 158.1 dB wrt 1 A/m, which may be compared with the value of -154.7 dB for standard ambient nighttime conditions.

In a further test, a calculation was made with all segments having the $\chi = 79.5^o$ electron profile yield an attenuation of -156.6 dB. When all segments were given the $\chi = 110^o$ profile, the result was -159.6 dB. In Table 4-3 some results of the latter two calculations are shown segment-by-segment along with comparisons of the simulated SPE profiles with ambient nighttime conditions.

These results indicate that there is a potentially important effect of variation of solar zenith angle along the ELF transmission path during a solar particle event.

Table 4-2 Calculated Field Strengths WTF - Norway for SPE of 4 Aug. 1972. Variations in Electron Density with Solar Zenith Angle

Solar Zenith	Path Segment	Calculated Field Strength (75 Hz (dB wrt 1A/m)	Calculated Change from Ambient Night (dB wrt 1 A/m)
79.5°	Whole path	- 156.6	- 1.9
110.°	Whole path	- 159.6	- 4.9
79.5°	0 - 2900 km	-158.1	- 3.4
89.5°	2900 - 3300		
95°	3300 - 4400		
110°	4400 - 6000		

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Table 4-3 Calculated Field Strength Decreases for the Path Segments WTR - Norway. Comparison of Modeled SPE Daytime and Nighttime Profiles with Ambient Nighttime Condition

Path Segment	Field Strengths in dB wrt 1 A/m				
	Ambient Night	$\chi = 79.5^{\circ}$	Difference from Ambient Night	$\chi = 110^{\circ}$	Difference from Ambient Night
0 - 200 km	- 134.2	- 129.0	+ 5.2	- 130.3	+ 4.8
200 - 1000	- 7.8	- 8.7	- 0.9	- 9.1	- 1.3
1000 - 1800	- 3.4	- 4.2	- 0.9	- 4.5	- 1.2
1800 - 2900	- 3.1	- 4.4	- 1.3	- 4.9	- 1.8
2900 - 3300	- 0.9	- 1.3	- 0.4	- 1.5	- 0.6
3300 - 4400	- 2.8	- 4.6	- 1.8	- 5.1	- 2.3
4400 - 5800	- 2.2	- 3.8	- 1.6	- 4.4	- 2.2
5800 - 6000	- 0.4	- 0.6	- 0.2	- 0.7	- 0.3
TOTAL	- 154.3	- 156.6	- 1.9	- 159.6	- 4.9

4.2 Effective Collision Frequencies

Ion masses and mobilities affect the conductivities, but are not considered to change as ion species change with altitude. In this section the effect of this assumption is considered.

The ELF waveguide mode computer program developed at the Naval Ocean Systems Center (NOSC) takes the ion conductivities $\sigma_{\pm}$ to be

$$\sigma_{\pm} = \frac{N_{\pm} e^2}{M_{\pm} \nu_{\pm}} \tag{1}$$

where e is the electronic change, $N_{\pm}$ is the ion density, $\nu_{\pm}$ is the collision frequency and $M_{\pm}$ is the mass of the positive or negative ion. At low altitudes the conductivity can also be expressed in terms of the ionic mobility, K,

$$\sigma = N\, e\, K \tag{2}$$

Hence, the collision frequency can be related to the ionic mass and the ionic mobility by

$$\nu = e/KM \tag{3}$$

In previous calculations, the ion collision frequency below 100 km has been taken to be independent of the mass and to vary with altitude h as 1.07×10^{10} and 8.00×10^{3} at h = 0 and h = 100 km, respectively. The positive and negative ion collision frequencies were assumed equal. Both ion masses were taken to be 32 amu. Since it is known that the masses of the positive and negative ions at low altitude may be ~ 100 amu, some concern has been expressed as to the effect of variation of the ion mass as a function of altitude.

Expressing the conductivity in the form given in Equation (1) implies at first glance a 1/M dependence on ionic mass. However, the collision frequency depends on mass as $M^{-1/2}$ because of the mass dependence of the mobility. Hence, the conductivity should vary as $M^{-1/2}$. This dependence is best determined by using Equation (3) to relate νM to the mobilities and to examine the dependence of the ionic mobility on mass.

The mobility of ions as a function of temperature, T, and pressure, P, is usually expressed as

$$K(T,P) = K^o\left(\frac{T}{273}\right)\left(\frac{760}{P}\right)$$

where T is in ^oK and P is in Torr, and K^o is the reduced mobility at atmospheric pressure and 273K. Table 4-4 shows the measured values of the reduced mobilities of the hydronium ions as a function of the mass of the ions.

For a more complete discussion of the mobilities of atmospheric ions in air based on both laboratory and in situ measurements, see Meyerott and Reagan (1978). It can be seen from Table 4-4 that the total range of the reduced mobility of the atmospheric ions in the mass range from 19 to 127 is only 2.7 to 1.8 cm^2/volt-sec.

In order to incorporate an estimate of the expected νM value into the NOSC ELF waveguide-mode program, it was decided for convenience to keep the mass of the positive and negative ions fixed at the present value 32 amu and to introduce an effective collision frequence, ν_e, adjusted to relate to the mobilities according to Equation (3). In Table 4-5 is presented the expected masses of the positive ions and their reduced mobilities as a function of altitude. These expected mass values have been taken from Smith and Church (1977). Also shown in Table 4-5 are the effective collision frequencies calculated from Equation (3). The mobility as a function of altitude was calculated using the reduced mobility K_+^o shown in Table 4-5 and the atmosphere temperature and pressure for the atmosphere as given by Johnson (1961). Also shown in Table 4-5 for comparison is the collision frequency as a function of altitude determined by the previously used expression $1.07 \times 10^{10} \exp(-0.1411h)$.

Table 4-4 Measured Hydronium Ion Mobilities*

Ion $H_3O^+ \cdot (H_2O)_i$		Reduced Mobility (cm^2/volt-sec) Bricard, et al. (1972)	Dotan, et al. (1976)	Young & Falconer (1972)	Huertas, et al. (1974)
i	Mass	Air	O_2	N_2	Air
0	19	-	2.75 ± 0.14	2.17	-
1	37	-	2.28 ± 0.11	2.4	-
2	55	-	2.13 ± 0.11	2.2	-
3	73	2.1		2.1	2.05
4	91	-		2.1	1.9
5	109	-			1.8

* The authors are indebted to R. Turco for this table.

It can be seen from Table 4-5 that the effective collision frequencies are ~ 1.5 times those previously employed.

The effect of this change was, however, small in a special test run for SPE conditions. A run was made with electron and ion profiles derived from data obtained at 5 August 1972 1254 UT used over the transmission path from WTF to Tromso. With the previous collision frequency profile, the resulting attenuation was - 156.9 dB wrt 1 A/m at 75 Hz. The new effective collision frequencies produced a smaller attenuation - 156.7 dB.

Table 4-5 Effective Collision Frequence, ν_e

h (km)	M_+ (amu)	K_+^0 (cm^2/volt-sec)	ν_e (sec^{-1})	Previous values of ν 1.07×10^7 exp (-01411h) (sec^{-1})
0	127	1.8	1.58×10^{10}	1.07×10^{10}
10	127	1.8	5.37×10^{9}	2.61×10^{9}
20	127	1.8	1.14×10^{9}	6.37×10^{8}
30	100	1.8	2.33×10^{8}	1.55×10^{8}
40	100	1.8	5.19×10^{7}	3.79×10^{7}
50	80	2.1	1.23×10^{7}	9.23×10^{6}
60	80	2.1	4.03×10^{6}	2.25×10^{6}
70	55	2.1	1.05×10^{6}	5.49×10^{5}
80	55	2.1	1.52×10^{5}	1.34×10^{5}
90	32	2.3	4.39×10^{4}	3.27×10^{4}
100	32	2.3	2.96×10^{3}	8.00×10^{3}

It can be seen from Table 4-5 that the effective collision frequencies are ~ 1.5 times those previously employed.

4.3 Effect of Increased Positive Ion Densities due to Bremsstrahlung X-Rays

In an earlier report (Imhof, et al., 1977) the nighttime ambient field strength for the path to Connecticut was calculated to be:

$$- 145.2 \text{ dB wrt } 1 \text{ A/m at } 75 \text{ Hz},$$

as indicated earlier in Table 3-4.

Using the spectrum of the electron precipitation deduced for 1 November 1972 (0405 UT), new ELF field strength calculations have been made with the path segmentation described in the previous report (Imhof, et al., 1977). In the present calculations, proper attention has been given the ionization at low altitudes due to bremsstrahlung X-rays from the precipitating electrons. The ion pair production rates from the X-rays exceeded those of the cosmic rays above 35 km, and X-rays were the major ionization source between 35 km and 62 km. Above 62 km ionization from electrons dominates, see Figure 4-2. The resulting N_+ densities, calculated as described earlier, varied between 1.031×10^4 cm^{-3} at 60 km and 7.2×10^3 cm^{-3} at 30 km, factors of ~ 5 and ≈ 2 above the ambient concentrations. The N_+ profile was smoothly joined with the N_e profile at 85 km as in Figure 4-3.

The computed result using these input parameters over the complete WTF to Connecticut path was:

$$- 143.5 \text{ dB wrt } 1 \text{A/m at } 75 \text{ Hz},$$

an enhancement of + 1.7 dB over ambient conditions.

Similar calculations for the case of 1 Nov. 72 made by (Imhof, et al., 1976) also indicated an enhancement ($\approx$ + 2.5 dB), but those calculations did not include any contribution from bremsstrahlung X-rays to the ionization. One can therefore conclude that inclusion of increased positive ion densities (due to X-rays) especially between 30 and 65 km contributes to the attenuation of the ELF signal strength. However, the increase in the ELF excitation factor for these electron and ion profiles is still large enough to offset the increase in the attenuation rates, as shown in Table 4-6. It may be noted that the computations made in 1976 used a more simple path segmentation. The ambient nighttime value at 75 Hz (- 145.8 dB) and other computations differ from those made in 1977 and 1978 by approximately 0.5 dB.

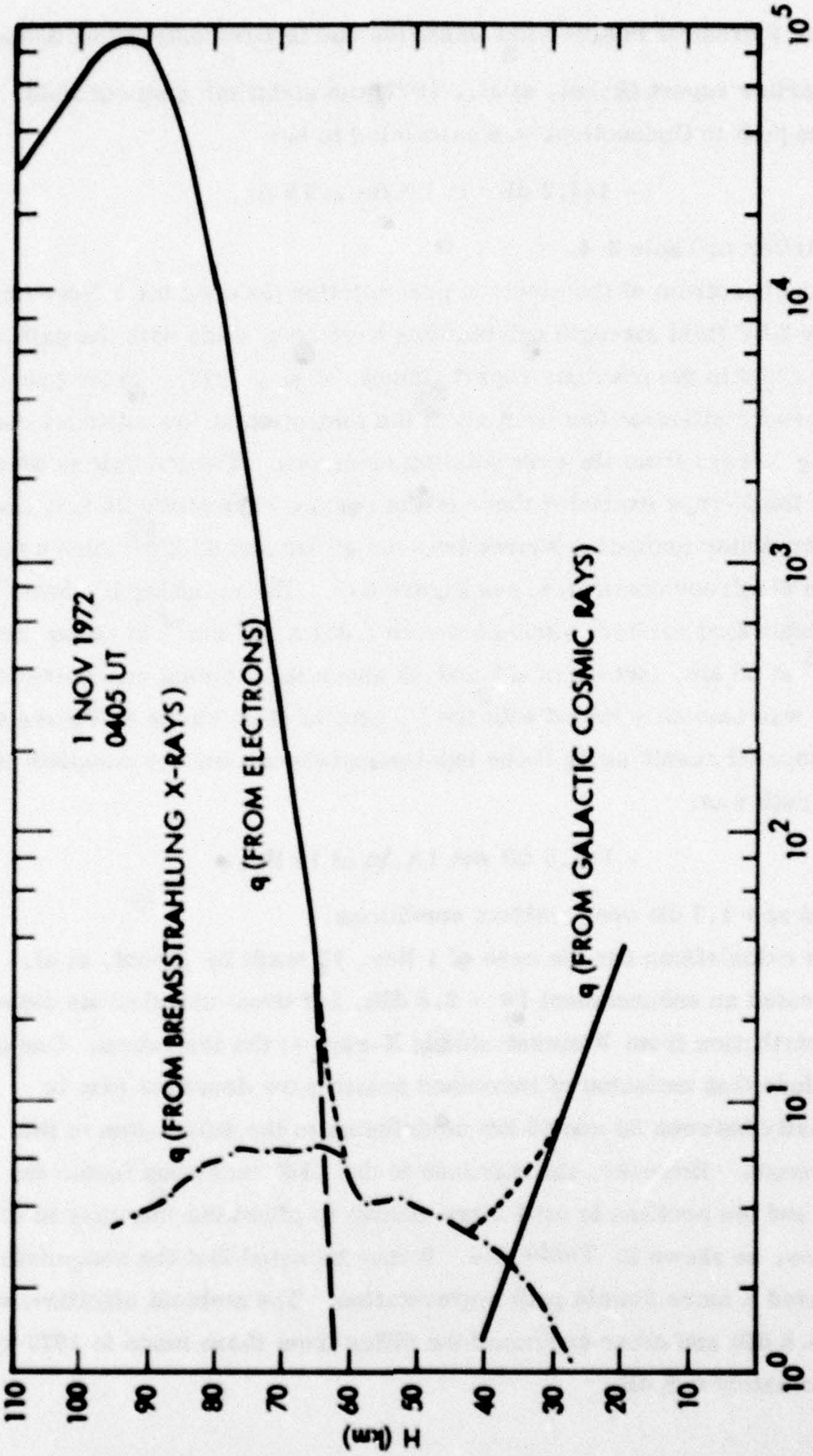

Figure 4-2 Ion pair production rate profiles for the nighttime electron precipitation event of 0405 UT 1 November 1972

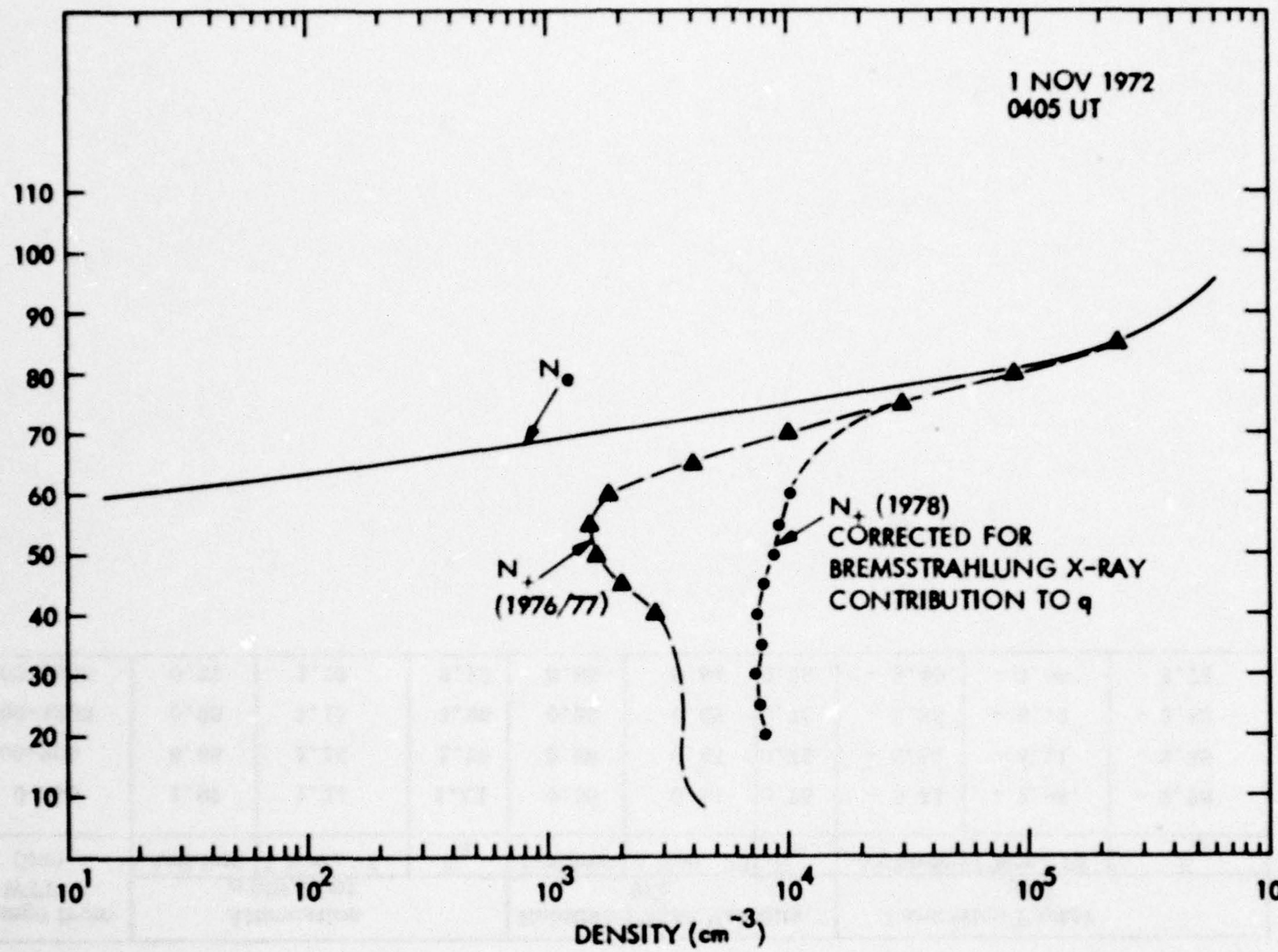

Figure 4-3 Electron and ion density profiles for the nighttime electron precipitation event of 0405 UT 1 November 1972. Positive ion profiles are shown both with and without the brehmsstrahlung x-Ray contribution.

Table 4-6 Calculated Propagation Characteristics at 75 Hz for Nighttime Propagation from WTF to Connecticut

Range from WTF (km)	Attenuation α (dB/Mm)			Relative Phase Velocity v/c			Excitation Factor (dB)		
	Ambient	1 Nov. 72	E_s	Ambient	1 Nov. 72	E_s	Ambient	1 Nov. 72	E_s
0-300	1.07	1.31	1.83	0.85	0.84	0.75	- 5.44	- 2.98	- 3.78
400-900	0.95	1.16	1.78	0.86	0.85	0.75	- 5.54	- 4.11	- 3.85
1000-1300	0.93	1.15	1.90	0.86	0.85	0.75	- 5.55	- 3.12	- 3.83
1400-1600	0.97	1.23	2.13	0.85	0.84	0.75	- 5.49	- 3.06	- 3.76

4.4 Effects of Sporadic E Layers

Earlier calculations (Imhof, et al., 1976, 1977) have shown that sproadic E (E_s) layers may be an important cause of ELF attenuation, and that the attenuation is very sensitive to the height of the E_s layer superposed on the ambient nighttime conditions. Independently, Barr (1977) has studied the effects of sporadic-E on the nocturnal propagation of ELF waves He showed that the presence of nocturnal sporadic-E produced marked maxima and minima in the propagation characteristics of ELF radio waves. He considered that these maxima and minima are produced by interference between the ELF waves reflected from the lower nighttime ionosphere and the ELF waves which penetrate this region to be reflected from the sporadic ionization above. These results may explain the marked variability of nocturnal ELF propagation observed by Bannister (1975) and Davis (1974).

The need for further and more complete investigations of the possible influence of E_s layers upon ELF propagation has been emphasized by some of our recent calculations based on the electron density profiles measured by Voss (1977). For these calculations the E_s layer measured by Voss was moved up in altitude so as to peak at 118 km instead of at 105 km. For this profile, shown in Figure 4-4, positioned over a part of the path (400 to 900km) from the WTF transmitter to the Connecticut receiving station, the computed signal strength was

- 145.7 dB wrt 1A/m at 75 Hz,

a value which is lower than the ambient signal by 0.5 dB.

The propagation characteristics for this calculation are given in Table 4-6 in column headed E_s where again it may be noted that the attenuation factors are increased over the ambient night values. These increases are partially offset by increases in the excitation factors.

Clearly significant variation in signal strength can result from the type of sporadic E layers that are sometimes measured.

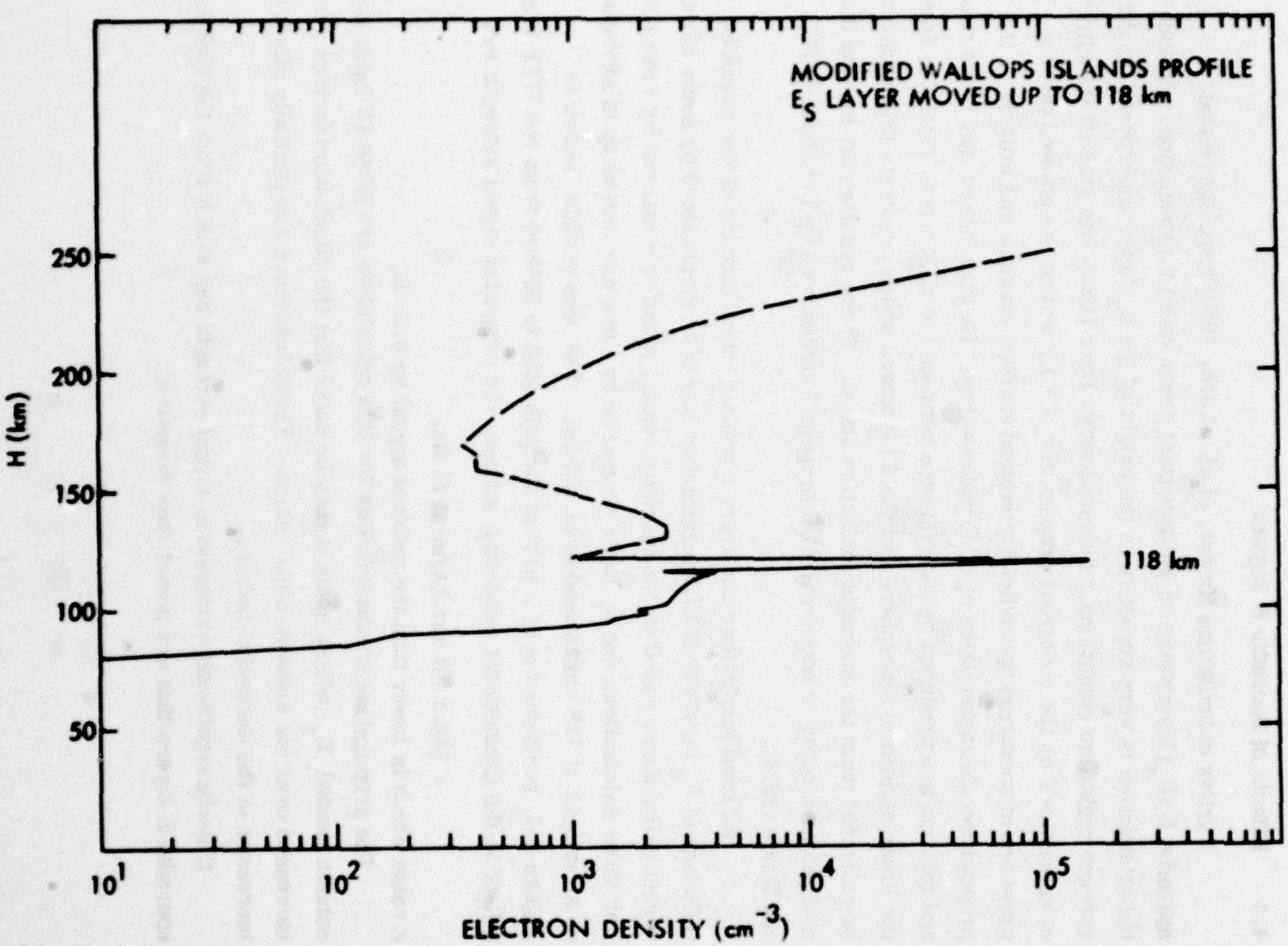

Figure 4-4 The standard nighttime ambient electron density profile with a superimposed experimental sporadic E layer profile due to Voss (1977).

Section 5
SUMMARY

During the Greenland Sea exercise, special coordinated measurements of the precipitating electrons and protons were performed during 92 passes of the satellite 1972-076B across the region of interest. Significant fluxes of precipitating electrons were measured on many of the passes, and unusually high intensities were observed on several occasions, two of which were selected for special study. The ELF signal strength data were provided by P. R. Bannister at the Naval Underwater System Center, New London, Connecticut.

Based on the coordinated ELF signal strength/energetic particle input measurements, a search was made for possible correlation between electron precipitation and ELF signal strength. From this investigation, including a separation of local noon and midnight data, no evidence was found for a consistent variation between the two parameters. This finding may partly reflect the uncontrolled and variable receiving conditions during the Greenland Sea exercise.

For two of the major electron precipitation events observed in the April-May 1977 Greenland Sea exercise, detailed analyses were performed of the electron energy spectra and intensities and of the resulting energy deposition profiles. For each of the electron density profiles, calculations of the ELF signal strengths were performed with the waveguide-mode computer program developed at the Naval Ocean Systems Center. From these calculations taken together with computations for other events, it became clear that the received signal may either increase or decrease, depending upon the spatial extent and location of ionization. The predicted effects of a single relativistic electron precipitation event are not severe, but due to their frequent occurrence, they may provide the opportunity to verify experimentally the predicted effects of more severe and rarely occurring phenomena such as solar particle events. For a more precise evaluation of their continued role in regard to ELF propagation, the acquisition and analysis of data on more coordinated passes should be performed.

For electron precipitation events, attempts were made to take better account of the full transmission geometry. The calculations were performed with position-dependent ionospheric electron and ion profiles for the satellite pass on 26 March 1976 during an

electron precipitation event. During that pass, two electron energy spectra were deduced and energy deposition rates and electron and ion density profiles deduced for both spectra. Assuming that the electron precipitation occurs uniformly along the L shells at all longitudes covered by the ELF paths under study, the two sets of ionospheric profiles were applied to the various portions of the propagation paths. The calculations so performed provided very good agreement with the measurements at Maryland and Tromso, whereas for Thule and Pisa the results were less satisfying. The lack of agreement may indicate that ambient nighttime conditions were not applicable to the entire paths and that in general more complete information is needed all along a propagation path.

Additional calculations were made for solar particle event (SPE) conditions, including for the first time daytime conditions. Specifically, electron and ion density profiles for the SPE of 4 August 1972 at 1144 UT were used. Electron densities above 59 km were derived from incoherent scatter radar observations made at Chatanika. Electron and ion densities down to 40 km were calculated using a model developed by Gunton, et al. (1977) and ion densities below 40 km were calculated assuming loss of charge by ion neutralization only. The results, calculated for daytime conditions, indicated slightly more attenuation than earlier calculations for SPE nighttime conditions. In other calculations for SPE events, a considerable sensitivity to changes in ion density profiles below 35 km was demonstrated.

The effect of variation of solar zenith angle and ion chemistry over a long ELF propagation path from WTF to Tromso under SPE conditions was found to have a significant effect on ELF signal strength at the receiver.

The waveguide mode computer code originally used 32 amu for ionic masses to compute conductivities at all altitudes. When a more realistic variation of ionic mass was introduced, the resulting attenuation for SPE conditions over the path from WTF to Tromso was little changed.

During an electron precipitation event bremsstrahlung x-rays are produced which penetrate the atmosphere and can produce ion production rates between 35 and 60 km greater than those of cosmic rays. In one such case inclusion of the x-ray source led to an increase in attenuation over a nighttime path from WTF to Connecticut.

In a further study of sporadic E layer effects, an experimental profile superimposed on ambient nighttime conditions at 118 km led to a reduction in received signal strength over the WTF to Connecticut path.

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